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MONTHLY WEATHER REVIEW

JAMES E. CASKEY, JR., Editor

Volume 85
Number 6

JUNE 1957

Closed August 15, 1957
Issued September 15, 1957

ON THE CONSERVATION OF FINITE-DIFFERENCE ABSOLUTE VORTICITY IN BAROTROPIC FORECASTS

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[Manuscript received April 12, 1957]

ABSTRACT

In solving the differential equations used in numerical weather prediction, one resorts to the use of finite-difference techniques. In the barotropic model it is assumed that the absolute vorticity is conserved. Even though the differential form of the vorticity equation insures conservation, the finite-difference form may not. The purpose of this study is to test this assumption in order to find out how serious truncation errors really are. The results indicate that the finite-difference absolute vorticity is reasonably well conserved, at least up to 48 hours.

1. INTRODUCTION

In the barotropic forecasts made by the Joint Numerical Weather Prediction Unit (JNWP) the absolute vorticity is assumed to be conserved, or:

$$\frac{d\eta}{dt}=\frac{d}{dt}(\nabla^2\psi+f)=0 \tag{1}$$

where η is the absolute vorticity, ψ is the 500-mb. stream function, and f is the Coriolis parameter. At JNWP the initial stream-function values used in the barotropic forecast are obtained using a method developed by Shuman [1] for solving the "balance equation,"

$$\nabla^2\phi=f\nabla^2\psi+2\left[\frac{\partial^2\psi}{\partial x^2}\frac{\partial^2\psi}{dy^2}-\left(\frac{\partial^2\psi}{\partial x\partial y}\right)^2\right]+\frac{\partial\psi}{\partial y}\frac{\partial f}{\partial y}+\frac{\partial\psi}{\partial x}\frac{\partial f}{\partial x} \tag{2}$$

where ϕ is the geopotential. In actual practice, the relative vorticity is approximated by the finite-difference vorticity or

$$\nabla^2\psi\approx\mathbf{\nabla}^2\psi=\frac{m^2}{d^2}(\psi_1+\psi_2+\psi_3+\psi_4-4\psi.) \tag{3}$$

where $\mathbf{\nabla}^2$ is the finite-difference Laplacian, m is the map factor, and d is the mesh length.

Since a method for obtaining exact solutions for most of the differential equations used in describing atmospheric processes is not known, one customarily resorts to the use of finite-difference techniques. The resultant approximations introduce errors called "truncation errors." Examination of cases wherein serious errors resulted in the barotropic forecasts made during the winter of 1956–57 led one to wonder if the absolute vorticity really was conserved. Perhaps truncation errors grew sufficiently to obscure the real physical developments. Even though the differential form of the vorticity equation expresses conservation, the finite-difference form may not insure it.

Substitution of the approximate equation (3) in (1) gives

$$\frac{d}{dt}\left[\frac{m^2}{d^2}(\psi_1+\psi_2+\psi_3+\psi_4-4\psi)+f+R\right]=0 \tag{4}$$

where R is the quantity which must be added to the right

[1] On temporary assignment to JNWP.

[2] Any opinions expressed by Lcdr. Hubert are his own and do not necessarily reflect the views of the Navy Department at large.

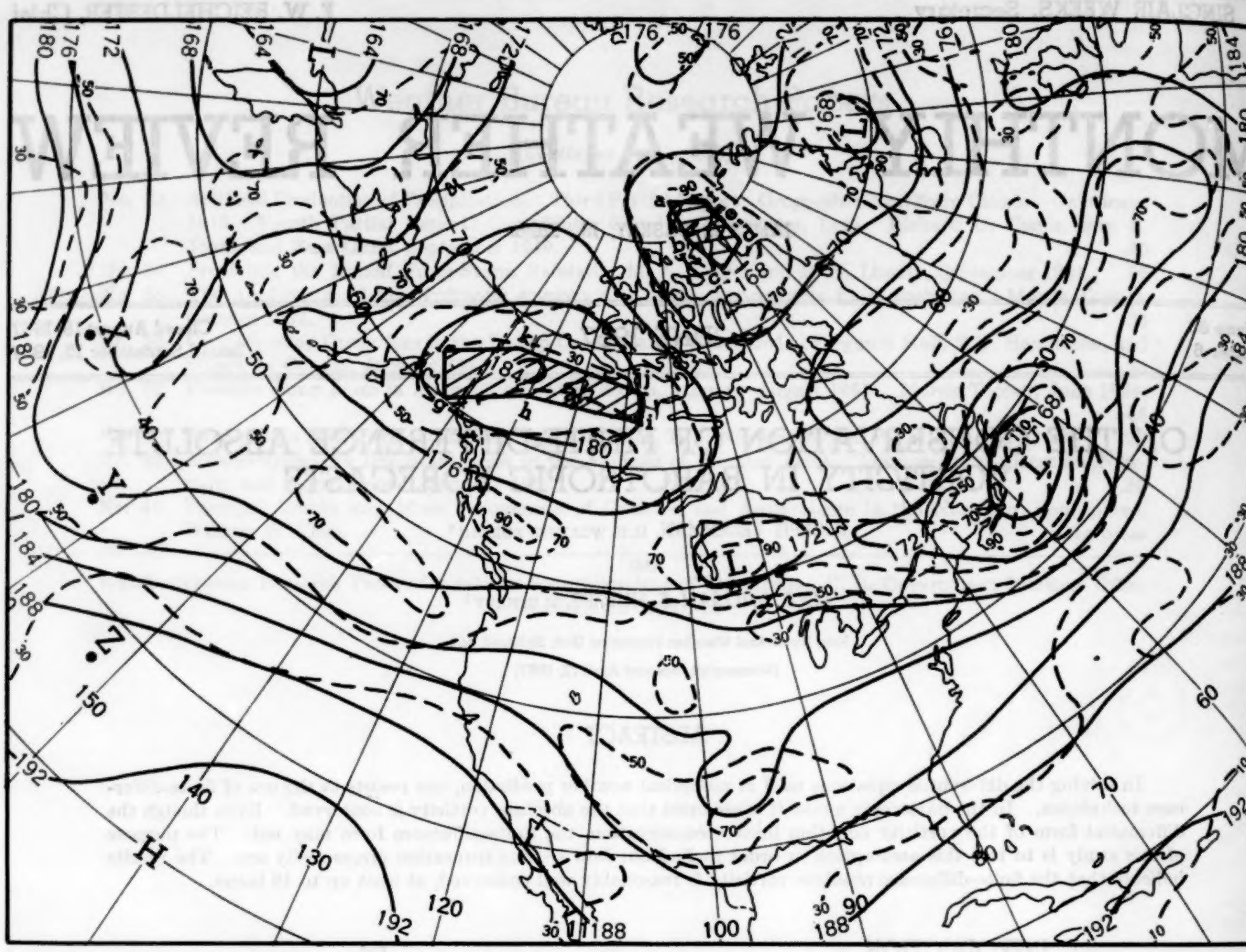

FIGURE 1.—The initial 500-mb. chart, 0300 GMT March 5, 1957. Solid lines are contours in hundreds of feet; dashed lines are absolute vorticity in units of 8×10^{-3} hr^{-1}. Trajectories were computed for points X, Y, and Z.

side of equation (3) to make it exact. Thus the finite-difference form of the vorticity equation becomes

$$\frac{d}{dt}(\nabla^2\psi+f)+\frac{dR}{dt}=0 \tag{5}$$

That is, in the finite-difference form the absolute vorticity is conserved only if dR/dt is equal to zero. The objective of this study was, therefore, to determine if the truncation errors are sufficiently large to make the absolute vorticity in the barotropic model nonconservative for forecasting purposes.

2. TRAJECTORIES OF PARCELS

During the progress of the barotropic forecast, fields of hourly 500-mb. stream-function values are stored on a "history tape." From these stored fields 72-hour trajectories of individual air parcels may be computed using a method due to Hubert [2]. The winds which are used in the trajectory computation are obtained by differentiating (at the location of the particle) a least squares cubic surface fit to 16 stream-function values surrounding the parcel being tracked. As a test of the accuracy of the cubic method, Hubert advected several parcels in a field held constant with time and found that the stream-function values along the trajectory departed from their initial values by only slight amounts over the course of several days.

Even though the trajectories are based upon predicted stream-function values which have been obtained from a barotropic forecast, they can be used to determine whether or not the finite-difference wind advects absolute vorticity at or near the same speed as the more accurate wind. For example, if it should be found that the absolute vorticity changes appreciably along the trajectory, one could argue that truncation errors really are serious.

Figure 1 shows the initial 500-mb. analysis for 0300 GMT March 5, 1957, and figures 2–4 the 24-, 48-, and 72-hour barotropic forecasts made from the initial chart. Points X, Y, and Z of figure 1 are three arbitrarily selected points for which trajectories were computed. The forecast locations of these points after 24, 48, and 72 hours,

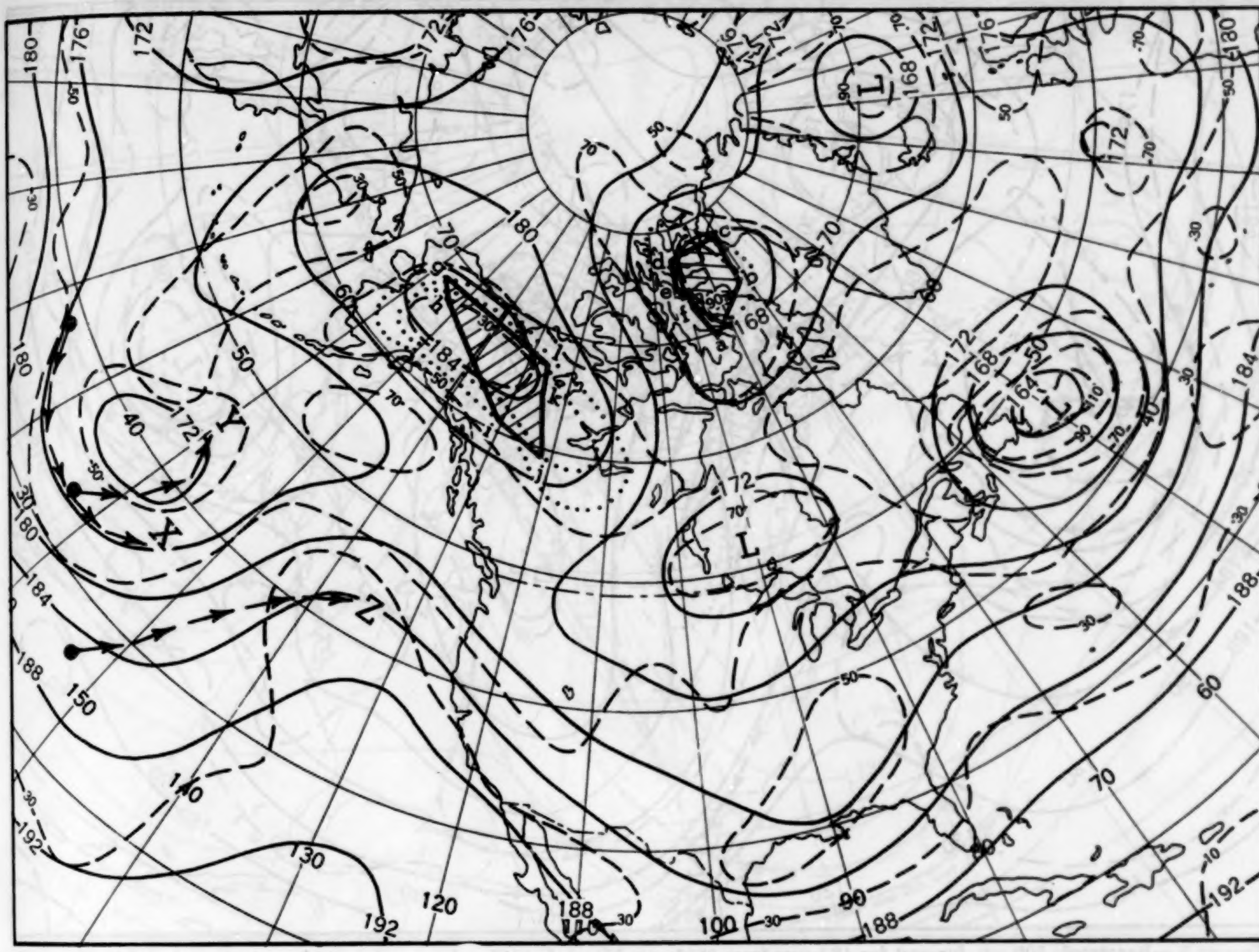

FIGURE 2.—Barotropic 500-mb. forecast for 24 hours from 0300 GMT March 5, 1957. Arrows show 24-hour trajectories of X, Y, and Z.

as well as the paths they followed, are shown in figures 2, 3, and 4. The absolute vorticity values for each field are indicated by dashed lines.

A summary of the initial and forecast absolute vorticities at 24-hour intervals along each trajectory is presented in table 1. Examination of the results reveals that the absolute vorticities of the points were fairly well conserved, but not perfectly. Another way to look at the error is to find how far the end points of the trajectories come from points in the grid where the absolute vorticities were within, say, 10 percent of the initial values. The "error" columns of table 1 show that even at 72 hours no point is off by as much as one mesh length (3° of latitude at 45° N.).

TABLE 1.—*Observed and forecast absolute vorticities in units of 8×10^{-3} hr^{-1} for parcels X, Y, and Z. Percentage change from initial absolute vorticities is also given. The number in the "error" column shows the distance, in mesh length, the end point of the trajectory would have to be displaced to make the absolute vorticity error 10 percent or less*

Point	March 5	March 6			March 7			March 8		
	η	η	Percent change	Error	η	Percent change	Error		Percent change	Error
X	76	70	8	0.0	57	25	0.7	65	14	0.9
Y	70	56	20	.4	60	14	.5	60	14	.9
Z	21	21	0	.0	30	43	.8	25	19	.4

3. CONSERVATION OF AREAS OF ABSOLUTE VORTICITY

The second experiment carried out in this study was somewhat different in that it dealt with the conservation of areas. In the JNWP barotropic atmosphere the divergence is zero so that the Area A of a closed curve on the earth's surface is conserved or

$$\frac{1}{A}\frac{dA}{dt}=\nabla\cdot\mathbf{V}=0 \qquad (6)$$

If one selects and follows a closed curve along which the absolute vorticity is constant, then in a barotropic atmosphere the area of the curve should remain unchanged from day to day and it should lie along the same absolute vorticity isoline.

Consider the polygon abcdef (fig. 1) which is located

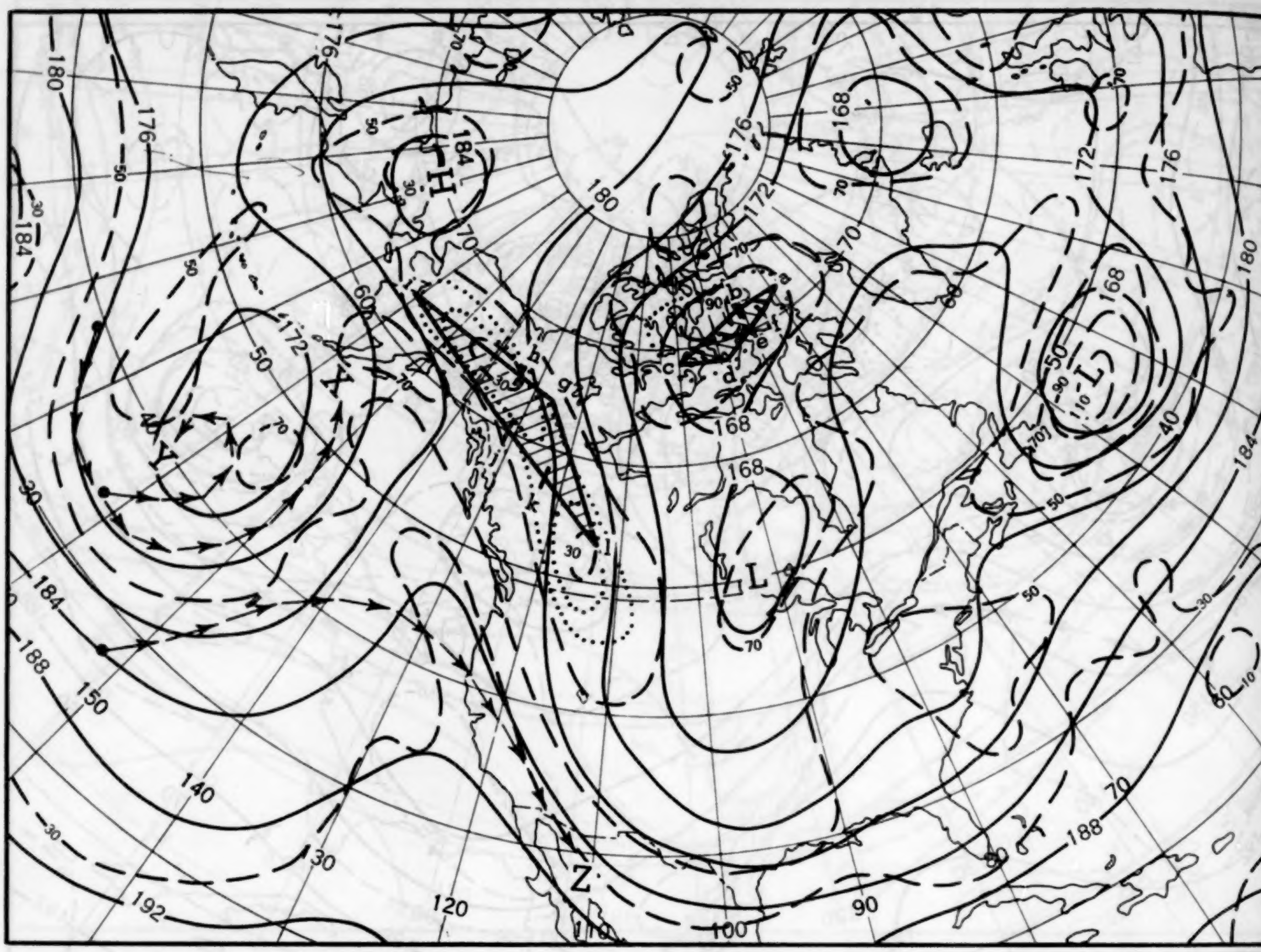

FIGURE 3.—Barotropic 500-mb. forecast for 48 hours from 0300 GMT March 5, 1957. Arrows show 48-hour trajectories of X, Y, and Z.

near latitude 75° N., longitude 75° W. at 0300 GMT March 5, 1957. The vertices of the polygon have been selected on the absolute vorticity isoline of 90, which in this case encircles a cyclonic maximum. (In order to simplify machine programing and computation, the absolute vorticity is expressed in units of 8×10^{-3} hr^{-1}.) Hourly positions of each of the points defining the polygon were computed with the trajectory code. By connecting the end points of the 24-hour trajectories for the six points, one obtains the location and shape of the polygon at the end of this period (see fig. 2). Similarly, the locations and shapes after 48 and 72 hours are given in figures 3 and 4. The areas of the polygons were measured, corrections were made for map scale, and the percentage change in areas computed. The results are shown in table 2.

TABLE 2.—*Area (in square inches) of polygon abcdef, and the percentage change from the initial area*

	Mar. 5	Mar. 6	Mar. 7	Mar. 8
Area	1.12	1.22	0.89	1.07
Percent change		8	12	4

The area abcdef at the end of 72 hours differed from its original size by only 4 percent. This difference is within the limits of measurement, and the table shows that the computational errors were not sufficient to change the area of polygon abcdef by very much. It is also possible to get some idea of the changes in absolute vorticity from figures 2, 3, and 4.

Figure 2 shows that all the points a, b, c, d, e, and f fell between the absolute vorticity isolines of 85 and 90. (The original value was 90.) In figure 3 all the points fell between the 80 and 90 isolines, and in figure 4 all the points fell within the 80 line. However, in the latter figure the 90 isoline has completely disappeared so that the area corresponding to this particular initial value has not been strictly conserved. On the other hand, at two grid points contained within the 72-hour polygon the absolute vorticity values were 85 and 87.

Let us now consider the polygon ghijkl, located near 65° N., 130° W. in figure 1. These vertices lie on the absolute vorticity isoline of 30 which encircles a minimum of absolute vorticity. Even though the polygon underwent

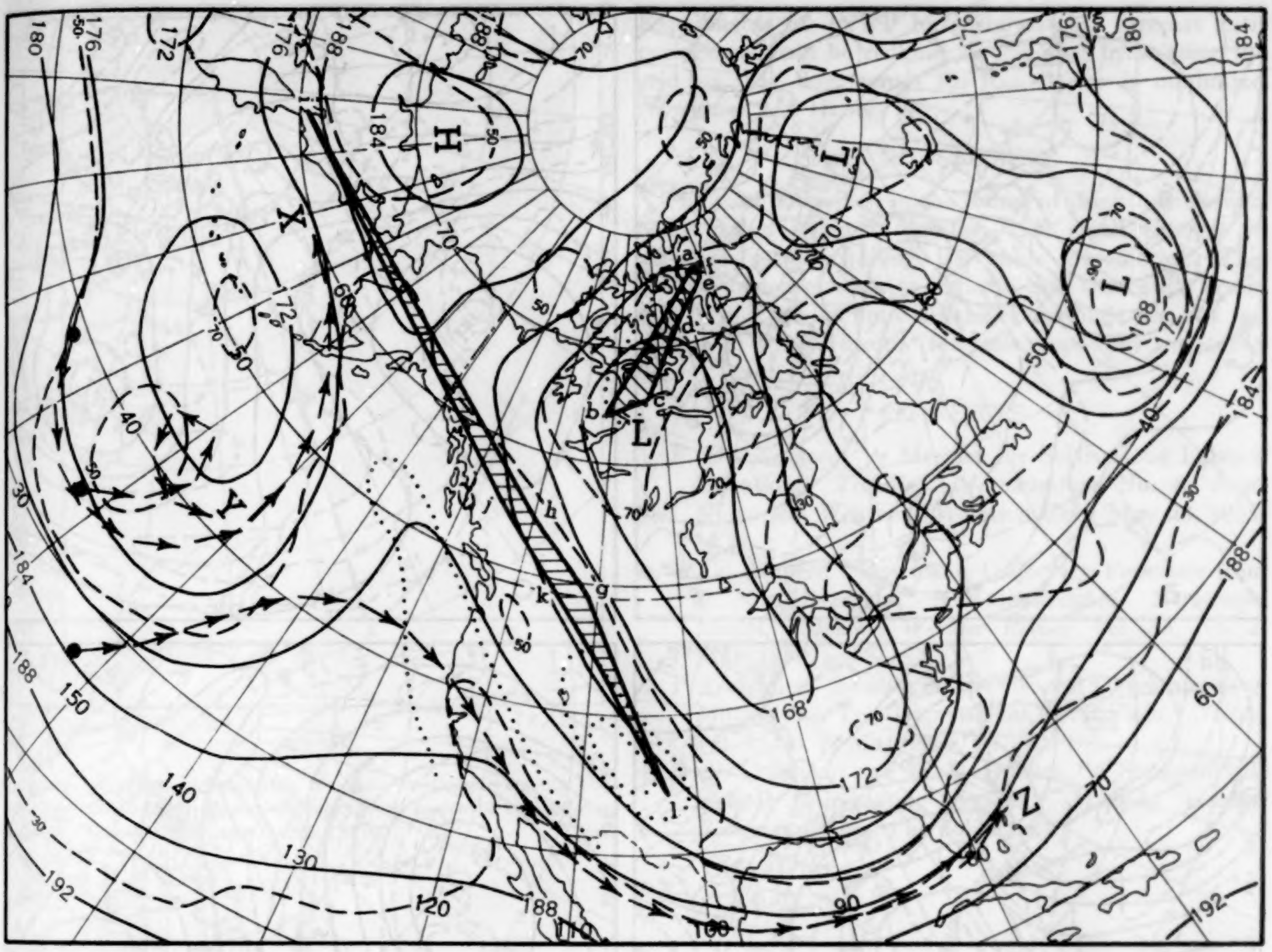

FIGURE 4.—Barotropic 500-mb. forecast for 72 hours from 0300 GMT March 5, 1957. Arrows show 72-hour trajectories of X, Y, and Z.

considerable displacement and deformation in the next 72 hours (figs. 2, 3, 4) the area was conserved to within 9 percent of its initial value. The results in this case are shown in table 3.

Referring to figure 2, one sees that except for point g the entire polygon fell inside the 40 absolute vorticity isoline. At 48 hours (fig. 3) the polygon was rather distorted, and at the same time the absolute vorticity pattern had two separate centers with minimum values near 30. By 72 hours (fig. 4) the polygon had been stretched almost beyond recognition; yet, the enclosed area differed from the original by only 7 percent. The 30 isoline had vanished from the neighborhood of the polygon, however, and in this case the absolute vorticity was not conserved for 72 hours. The mean value of the absolute vorticity over the polygon had increased to about 48.

TABLE 3.—*Area (in square inches) of polygon ghijkl, and percentage change from initial area*

	Mar. 5	Mar. 6	Mar. 7	Mar. 8
Area	3.39	3.11	3.08	3.64
Percent change		8	9	7

One gets the impression that the initial absolute vorticity of the second polygon was stretched out into such a long, narrow band that it was lost between grid points. In the course of the barotropic forecast, the field of $\nabla^2\psi$ is smoothed every 12 hours to eliminate the shorter wavelengths. This has the effect of wiping out narrow filaments of vorticity. Synoptic experience suggests that nature acts in much the same way; thin elongated ridges at the 500-mb. level have short life periods. Welander [3] has described the development of a deformation pattern quite similar to that obtained in the case of polygon ghijkl.

4. ANTICYCLOGENESIS OF MARCH 1, 1957

One of the characteristics of the 500-mb. barotropic forecasts during the winter of 1956–57 was excessive anticyclogenesis in mid-Pacific. The 48-hour forecast made from initial data for 0300 GMT March 1, 1957, gave a High with a central value of 19,600 ft. near 42° N., 153° W.; by 72 hours the central value had risen to 19,900 ft. and retrogression toward the west continued. These values turned out to be about 2000 ft. higher than

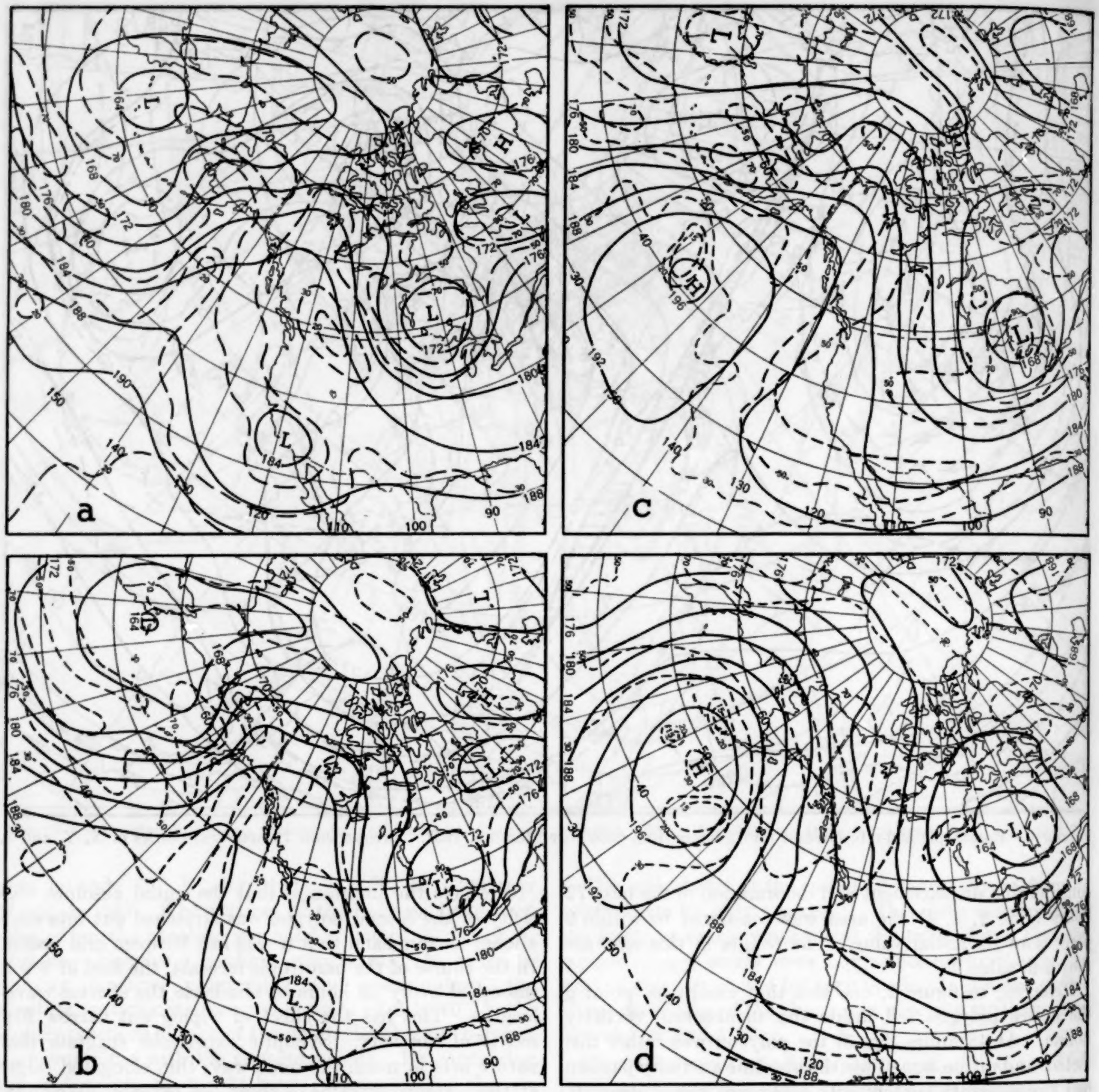

FIGURE 5.—500-mb. barotropic forecasts from 0300 GMT March 1, 1957: (a) for 12 hours, (b) for 24 hours, (c) for 48 hours, and (d) for 72 hours. Solid lines are contours in hundreds of feet. Dashed lines are absolute vorticity in units of 8×10^{-3} hr^{-1}.

observed. Did truncation errors play an important role in the excessive anticyclogenesis?

Figure 5 shows the sequence of forecast maps for this case while figure 6 shows the time variation of the lowest value of absolute vorticity that was moving into the neighborhood of the anticyclone's center. The changes in the minimum absolute vorticity indicate that strict conservation did not occur here. The 12-hour forecast chart had a minimum of 18, but values as low as 11 could be found in the 48-hour forecast and 14 at 72 hours. Truncation errors are offered as a partial explanation for this observed decrease in absolute vorticity. However, it does not appear that these errors were sufficiently large or spread over a great enough area to account for much of the anticyclogenesis. Rather, it seems that errors due to unrealistic boundary assumptions may have been of prime importance because there was strong inflow across the southern boundary throughout the forecast period.

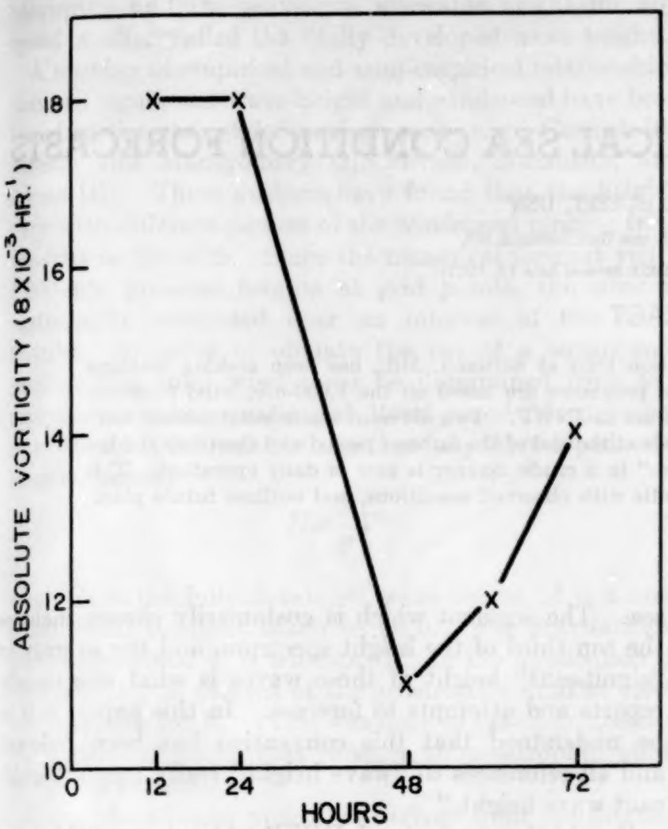

FIGURE 6.—Change in minimum absolute vorticity entering the Pacific anticyclone. Based on barotropic forecasts make from 500-mb. data for 0300 GMT March 1, 1957.

Experiments at JNWP have shown that forecast anticyclogenesis can be reduced in this area by shifting the grid so that flow across the boundaries is minimized (Cressman and Hubert [4]).

5. CONCLUSIONS

The tests conducted in the course of this study showed conservation of area together with small changes in absolute vorticity along the cubic trajectories. This limited evidence seems to indicate that truncation errors due to the use of finite-difference methods are not too serious in the barotropic forecasts, especially out to 48 hours.

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A PRELIMINARY REPORT ON NUMERICAL SEA CONDITION FORECASTS

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[Manuscript received April 19, 1957; revised June 18, 1957]

ABSTRACT

Since July 1956 the Joint Numerical Weather Prediction Unit at Suitland, Md., has been making machine forecasts of sea conditions on an operational basis. These prognoses are based on the 1,000-mb. wind forecasts derived from the two-level, thermotropic model currently in use at JNWP. Two different sea-forecast models have been tested to date. The first utilized only the forecast winds at the end of the forecast period and therefore yielded "fully developed waves." A model incorporating "duration" in a crude manner is now in daily operation. This paper describes both methods, compares the numerical results with observed conditions, and outlines future plans.

1. INTRODUCTION

In describing and forecasting sea conditions, one generally deals with two more or less distinct problems—wind-driven waves, often called "sea," and another class of waves called "swell." Swell is defined as waves which have moved outside of the locale in which they were generated, whereas wind waves are those presently in a specific generating area.

In the first machine forecasts of sea conditions attempted at the Joint Numerical Weather Prediction Unit (JNWP), only wind waves have been considered. The reasons for neglecting swell are primarily two; first, the total problem is thereby greatly simplified, and second, in most cases swell is a less important factor in the preparation of prognostic sea-condition charts. This does not mean that swell is always negligible. As a matter of fact, in some areas (e. g., subtropical high pressure cells) swell is frequently the only contributing factor, and more advanced forecast models will undoubtedly have to incorporate this feature.

Considering wind-driven waves alone, then, the principal parameters which define the height to which they will finally grow are windspeed, duration, and fetch. Obviously, a 50-knot wind blowing for only 10 minutes will not generate waves as high as the same wind blowing for a period of 10 hours. Similarly, a 50-knot wind flowing across a puddle 100 yards in diameter will not generate waves as high as it would on a lake 100 miles in diameter.

The "sea" at any particular location is actually composed of waves covering a wide band of heights and wavelengths. It has become more or less standard practice among oceanographers and forecasters to deal with a certain segment of the entire wave spectrum when attempting to describe and/or forecast the state of the sea. The segment which is customarily chosen includes the top third of the height spectrum, and the average or "significant" height of these waves is what one usually reports and attempts to forecast. In this paper, it is to be understood that this convention has been followed and all references to "wave height" really mean "significant wave height."

One of the products of JNWP which is available on a daily basis is a numerical forecast of the 1,000-mb. pressure heights at points on a 30×34 grid covering approximately two-thirds of the Northern Hemisphere. The grid interval is 381 km. at 60° N. From these forecast heights one can readily obtain the surface winds which serve as the basis for the sea-condition prognostication. A two-level model of the atmosphere developed by Thompson [1] is currently being used at JNWP to make the 1,000-mb. forecast.

Since the basic forecasts are an operational requirement placed on JNWP and are therefore run on a daily schedule, it was felt that sea-condition forecasts might turn out to be a relatively inexpensive byproduct. For this reason it was decided to undertake an investigation of numerical sea forecasting models wherein relevant parameters would be treated in decreasing order of importance. The machine forecasts described in this preliminary report represent the first phase of this investigation and are essentially an attempt to apply numerical methods to the subjective, prognostic technique developed in the Division of Oceanography, U. S. Navy Hydrographic Office.

2. FULLY DEVELOPED WAVES

Probably the simplest model which one can use for the numerical prediction of sea conditions assumes that both duration and fetch are infinite. Under these conditions the sea is said to be fully arisen. The height to which a wave will grow is assumed to be dependent only upon the

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windspeed and the maximum allowable height for any speed is often called the "fully developed wave height."

A number of empirical and semi-empirical relationships between significant wave height and windspeed have been found in the case of fully arisen seas (e. g., Cornish [2], Rossby and Montgomery [3], Pierson, Neumann, and James [4]). These authors have found that the heights vary with different powers of the windspeed ranging from the first to the fifth. Since the numerical forecast yields 1,000-mb. pressure heights at grid points, the wind is customarily computed over an interval of two mesh lengths. In order to obviate the use of a square-root routine (the total wind must be determined from two components) the equation of Rossby and Montgomery was selected for computing the fully developed sea-heights, namely:

$$H=\frac{A}{g}V^2 \tag{1}$$

where H is the fully developed wave height, A is a non-dimensional constant taken to be 0.3, g is gravitational acceleration, and V is windspeed. In the application of equation (1), 70 percent of the geostrophic wind at 1,000 mb. was used for V. (This was done to take into account the various elements that produce subgeostrophic winds at the sea surface.)

Using the 36-hour prognoses derived from the thermotropic model, numerical forecasts of fully developed wave heights were made at JNWP for several months. As one might expect, the results were far from good when compared with actual conditions. On the other hand, they were not completely discouraging either; in areas where the assumptions of unlimited fetch and duration were reasonably true, the predicted and observed wave heights agreed remarkably well, indicating that equation (1) is basically correct. The tendency was to predict high waves to be too high and low waves too low. These discrepancies are primarily due, it appears, to the assumption of infinite fetch and duration in the case of high waves, and to the neglect of swell in areas of weak winds where the waves were predicted to be too low.

Analyses prepared at the U. S. Fleet Weather Central (FWC), Washington, D. C., following the methods developed at the U. S. Navy Hydrographic Office (Schule and Ropek [5]) have been used to test the accuracy of the numerical computations. The FWC analyses are based primarily on ship observations; however, in areas of sparse data, continuity, and computations utilizing the prediction curves of Bretschneider [6] and others are used to fill in. In figure 1a is shown a chart of wave heights determined from equation (1) using the observed 1,000-mb. height field at 1500 GMT January 8, 1957, as input data. By comparing with the sea-condition analysis at 1230 GMT for the same day, figure 1c, one can readily see that in general the patterns are quite similar; however, the waves obtained from the numerical computation are much too high in the areas of strong winds.

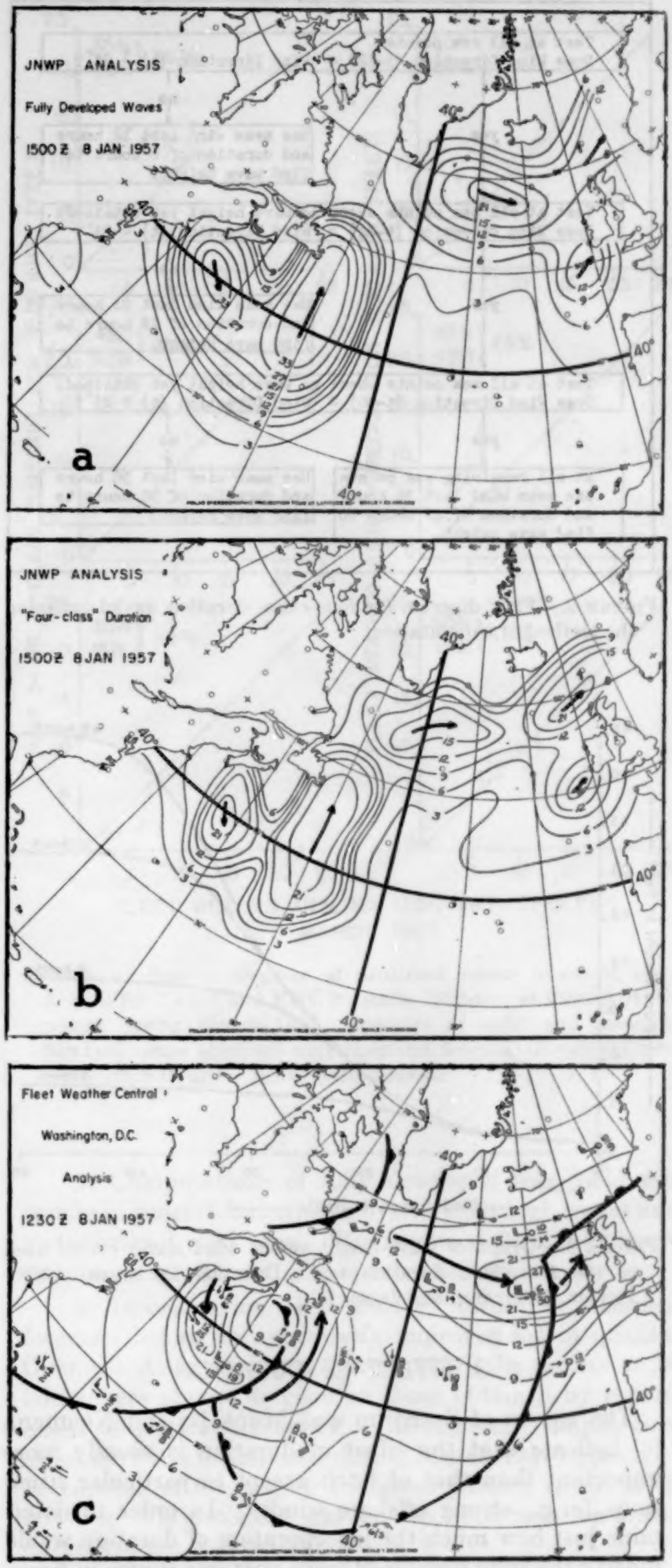

FIGURE 1.—Wave-height comparisons for January 8, 1957: (a) JNWP analysis of fully developed waves at 1500 GMT; (b) JNWP analysis at 1500 GMT using the four-class, duration model; and (c) Fleet Weather Central analysis for 1230 GMT. Wave heights in feet.

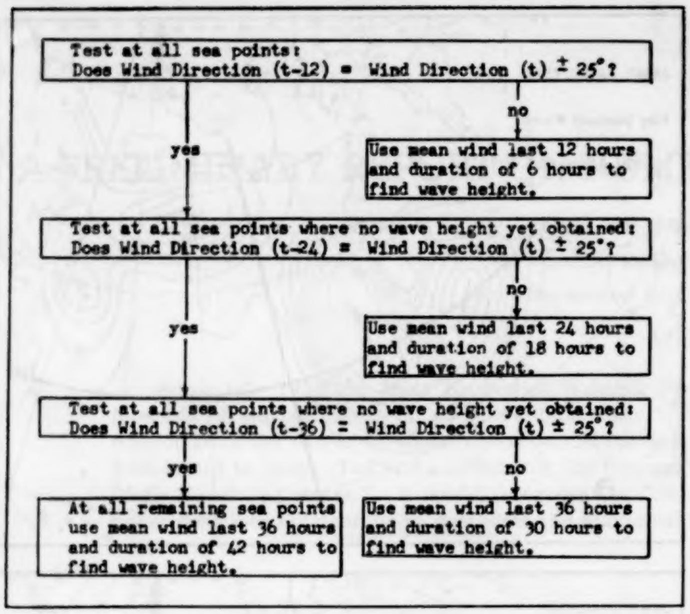

FIGURE 2.—Flow diagram for four-class, duration model outlining the method of computation.

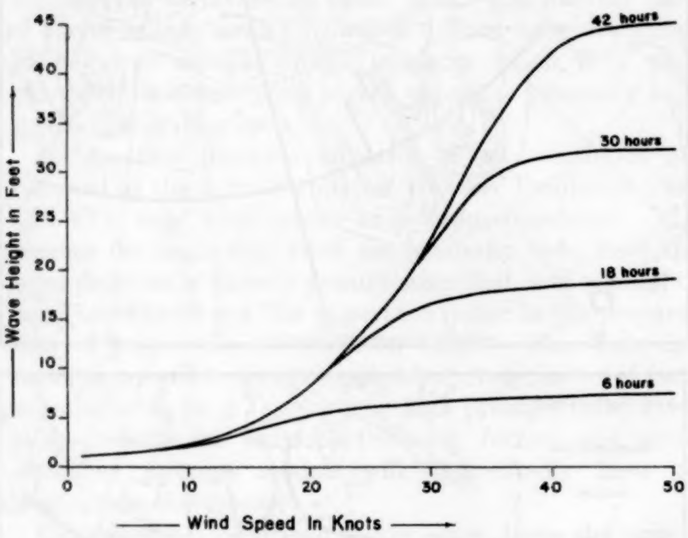

FIGURE 3.—Graph of wave-height versus wind speed curves used in the four-class, duration test. Duration in hours. (After Pierson, Neumann, and James [4].)

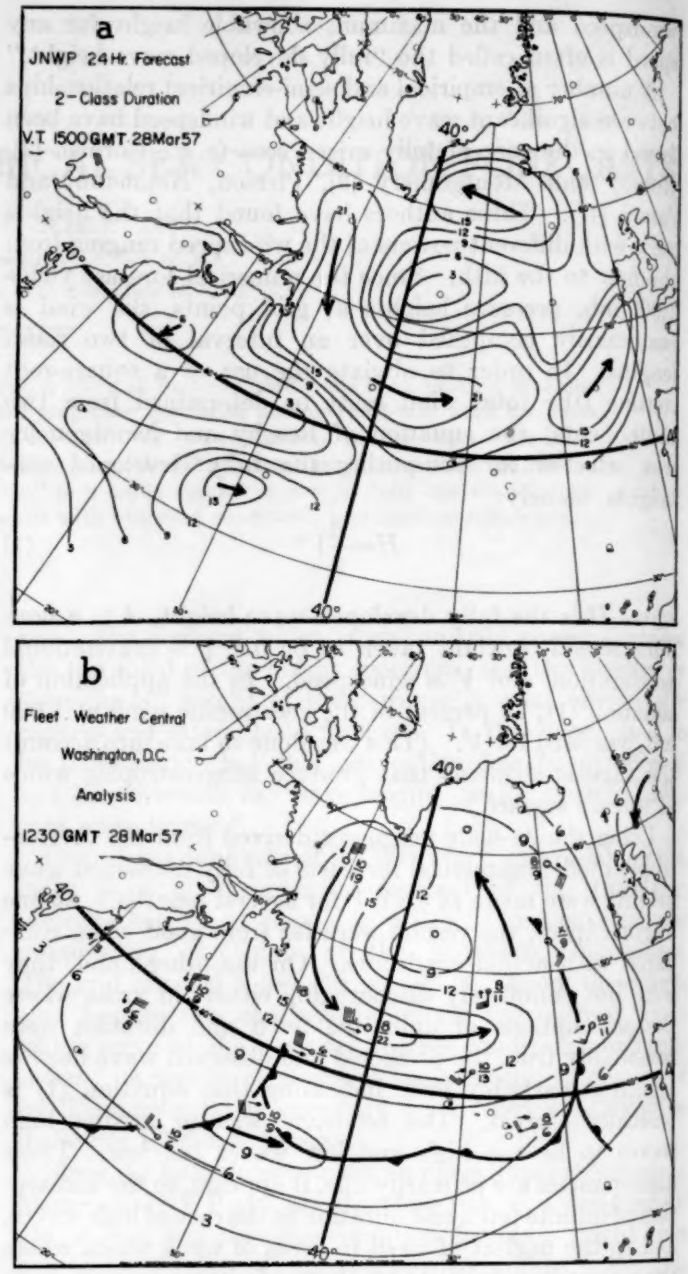

FIGURE 4.—(a) Example of a numerical, 24-hour wave forecast (two-class, duration) verifying at 1500 GMT March 28, 1957, and (b) Fleet Weather Central analysis of observed heights at 1230 GMT the same day.

3. EFFECT OF DURATION

The curves of Sverdrup and Munk [7] and Neumann [8] indicate that the effect of duration is usually more important than that of fetch except in particular situations (e. g., strong offshore winds). In order to determine just how much the incorporation of duration would modify the fully developed wave patterns shown in figure 1a, a duration model was tested on the same case. Four observed 1,000-mb. fields at 12-hour intervals prior to and including 1500 GMT January 8, 1957, were used as input data. In other words, it was assumed a priori that a perfect wind forecast was available in order to eliminate this source of error from the comparison.

The computational procedure for the "four-class" duration model is shown in the form of a flow diagram in figure 2. Time (t) represents the end of the forecast period; ($t-12$) is 12 hours earlier, etc. The wave height versus windspeed relationships for the four allowable duration times of 6, 18, 30, and 42 hours (from Pierson, Neumann, and James [4]) were stored in the computer. Figure 3 shows these same data plotted as four duration curves on

a chart having windspeed as the abscissa and wave height as the ordinate.

The results of the four-class duration computation are shown in figure 1b. All-in-all, the wave heights agree more closely with those observed than in the case of fully developed waves. In particular, the maxima are lower than those obtained from equation (1). The 21-foot maximum to the rear of the cold front off Boston is almost exactly reproduced by the numerical method. The maximum ahead of the occluded front is still computed to be too high; there is some doubt, however, about the analysis here, for no ship reports were received from the area of strongest southerly winds. The maximum west of Ireland split into two centers in the duration test; nevertheless, the overall correspondence is good. The improvement in the Pacific area (not shown here) was even greater, especially around a severe storm in midocean.

Throughout March 1957, 24-hour forecasts of wave heights based on an extremely simple, two-class duration model were made on an operational schedule. In this series of tests the 12- and 24-hour, 1,000-mb. forecasts were used to determine the wind speed and direction. If the wind shifted more than 25° in direction during the 12-hour interval, a duration of 6 hours was assumed to apply; otherwise, the duration was arbitrarily taken to be 24 hours. Figure 4 shows an example of a numerical forecast and the verifying analysis. A summary of the results obtained during March 1957 at three locations in the North Atlantic is shown in figure 5. The forecast and observed wave heights transmitted via facsimile from the U. S. Fleet Weather Central are presented for comparison.

Monthly mean values of forecast minus observed heights ($F-O$) divided by observed heights (O) have been determined for the three points. At latitude 55° N., longitude 15° W., the objective forecasts had a mean error of 43 percent compared with 19 percent for the subjective forecasts made at the Fleet Weather Central. This point is closest to the edge of the numerical forecast grid, and the predicted 1,000-mb. heights are apt to be in error here due to boundary influences. This might help to explain this difference; however, whatever the cause, the "hand" forecasts were clearly superior at this point. At the other two locations the numerical method (in spite of the crudeness of the model) was close to being competitive. Errors of 28 and 36 percent obtained for the JNWP forecasts compared with 25 and 29 percent for those from the weather central. It should be pointed out that there is a 2½-hour time difference between the end of the numerical forecast period and the observation time used in making the comparisons. Wave patterns can change appreciably in this time, and it may well be that the numerical method is truly competitive here.

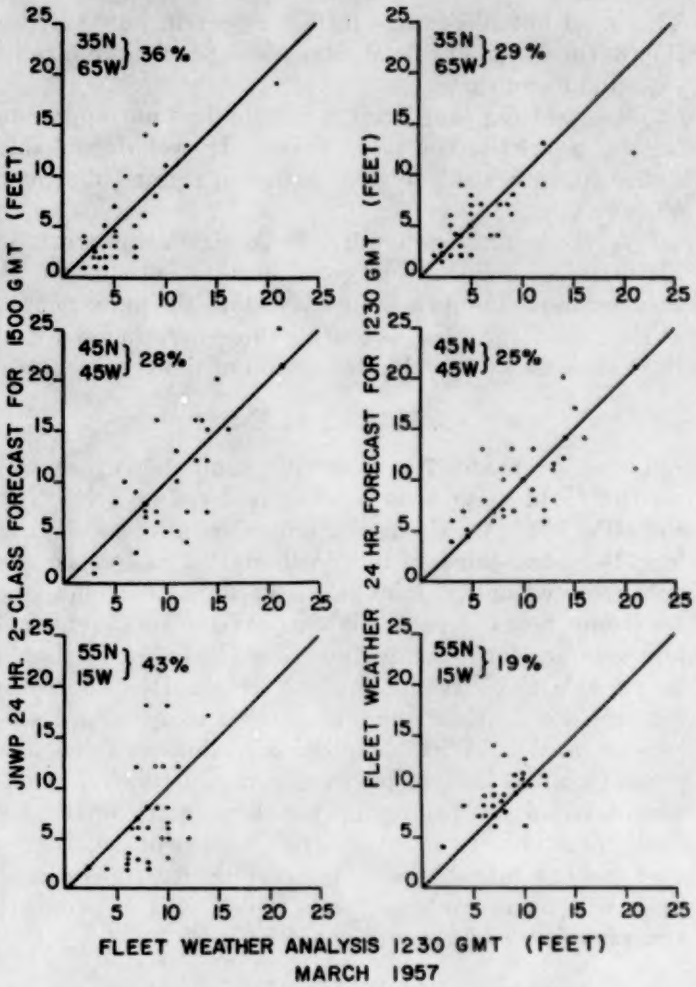

FIGURE 5.—Scatter diagram of predicted versus observed wave heights for JNWP and FWC forecasts (24 hour) at three Atlantic points during March 1957. Location of point and mean of forecast minus observed over observed heights, $(F-O)/O$, (percent) given in upper left of each diagram.

4. CONCLUSIONS

From the 9 months of cases which have been run at JNWP, the following somewhat preliminary conclusions are offered:

1. Computations of fully developed seas yield fair results in general, but tend to overforecast high waves and underforecast weak ones. The results at 24 and 36 hours are not competitive with subjective techniques.

2. Incorporation of "duration" into the numerical forecasts led to an appreciable improvement in quality. Over the Atlantic during March 1957, the results at 24 hours were almost as good as those obtained by experienced subjective forecasters. The extremely simple, two-class, duration model used during March 1957 appears to be capable of forecasting the gross pattern rather well; however, it is also clear that a closer determination of the duration time is desirable.

3. Any numerical forecast of sea conditions will be only as good as the numerical forecast of surface winds upon which it is based. To date, the machine forecasts of low-level flow patterns have not been as good as those prepared by the experienced synoptic meteorologist (even though the reverse may be true already at upper levels).

This need not discourage further research, however, for improvement in low-level numerical prediction can be expected to continue.

4. Assuming that fetch is infinite does not appear to be too restrictive in most cases. It would probably suffice to correct this approximation in regions of strong, offshore flow.

5. Neglecting swell can lead to significant errors in limited areas under special conditions. Any refined forecast technique should attempt to include the movement of at least the largest waves outside the generating area and treat their decay for a limited period of time.

5. FUTURE PLANS

The IBM model 701 electronic computer which was used in all of these tests is being replaced at JNWP by the IBM 704. On the 701, a numerical forecast of wave heights for two-thirds of the Northern Hemisphere's ocean area required only 5 minutes of machine time (once the 1,000-mb. fields were available). When low-level wind forecasts are forthcoming from the IBM 704, it should be possible to cover the entire Northern Hemisphere in 5 minutes and at the same time use a more refined sea-forecast model. With these considerations in mind, the present plan is first to program a model which will determine duration to the nearest hour and correct for fetch in the vicinity of the coasts. Because of the change-over to a new machine, wave forecasting on an operational basis will be discontinued at JNWP until a two-level atmospheric model is running on the IBM 704.

ACKNOWLEDGMENTS

The author would like to express his appreciation to Capt. W. E. Oberholtzer, Jr., USN, for his continuous encouragement during the progress of this study. The subjective forecasts used in the comparisons were prepared by the duty aerologists at the U. S. Fleet Weather Central, Washington, D. C. A number of very fruitful discussions were held with staff members of the Division of Oceanography, U. S. Navy Hydrographic Office, during the past year, and their suggestions for future lines of attack are most welcome.

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WEATHER NOTES

THE PATH OF THE KANSAS-MISSOURI TORNADO OF MAY 20, 1957

Introduction

May 20, 1957, was a day of many tornadoes in Kansas, Nebraska, Oklahoma, and Missouri. The most sensational and destructive of these was the Kansas-Missouri tornado, which took over 40 lives, injured about 200, and caused millions of dollars of property damage. The greatest concentration of destruction was in the suburban Kansas City, Mo., communities of Martin City, Hickman Mills, and Ruskin Heights, although destruction was continuous along the entire path of the tornado.

The study to follow is limited to features of the tornado as revealed by a survey of the damage path. The survey had the following objectives: (1) To ascertain path and path width; (2) to ascertain times of passage; (3) to note any unusual characteristics; (4) to obtain photographs; and (5) to interrogate witnesses. A preliminary survey was made by air, after which a more detailed ground survey was made.

Path and Path Width

The path of the tornado was examined by "section-lining" the area through which it passed; i. e., all section-line roads in the area were traversed and positions of the path determined to the nearest 1/10 mile. Slant width of the path was measured along section-line roads and then corrected trigonometrically to yield actual path width normal to the direction of motion. The path was arbitrarily taken as that portion in which major destruction occurred; e. g., uprooted and broken trees, collapsed buildings, etc. It did not include fringe areas where damage was minor, or where only fallout of debris occurred.

The path of the tornado is shown in figure 1. The first contact with the ground was about 2 miles southwest of Williamsburg, Kans. From there it continued to a point about 2 miles northeast of Knobtown, Mo. The path was a single one except near Homewood, Kans., where a second path lay parallel to and north of the main path. Average direction of motion was 59° (approximately east-northeast), but with the direction varying from 90° (east) north of Peoria, Kans., to 40° (approximately northeast) near Martin City, Mo. Length of the main path was 71 statute miles. Length of a secondary path near Homewood, Kans., was about 7 miles. Width of path varied from less than 1/10 mile to 4/10 mile. Table 1 shows path widths at various portions of the path. The letters refer to portions of the path as indicated on the scale at the bottom of figure 1.

One might have expected considerable skipping of the tornado along the path. However, such was not the case. With one exception, destruction occurred along every section-line road crossed by the tornado.

TABLE 1.—*Width of tornado along various portions of the path identified by letter in figure 1 (in miles)*

A	0.1 to 0.2	G	0.3	M	0.2 to 0.3
B	0.2 to 0.4	H	0.2	N	0.3
C	0.3 to 0.4	I	0.3	O	0.2 to 0.3
D	0.1 to 0.2	J	0.3 to 0.4	P	0.3 to 0.4
E	0.1 or less	K	0.2 to 0.3	Q	0.2
F	0.1 to 0.2	L	0.1 to 0.2		

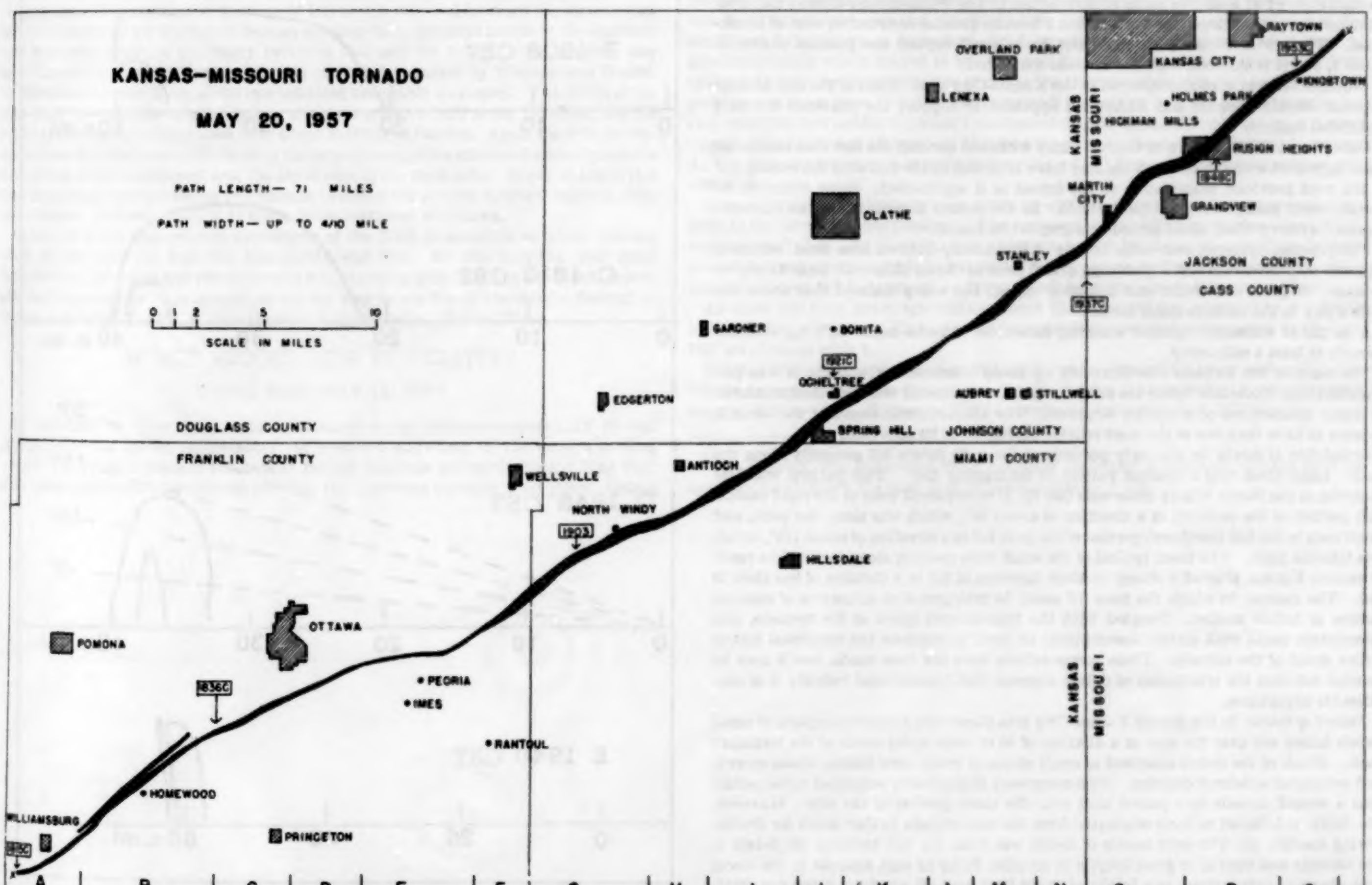

FIGURE 1.—Map of the tornado's path. Nearby cities, villages, and communities are shown. The lettered scale at the bottom of the map refers to remarks concerning path width given in table 1.

A check was made to determine if path width were related to topography. No such relationship was found. In some areas the path was wide in valleys and narrow on ridges. Elsewhere the reverse was true. There was no apparent tendency for the tornado to follow any topographic features; i. e., ridges, valleys, or rivers.

Times of Passage

Considerable difficulty was experienced in obtaining accurate times of the tornado's passage. Many witnesses were understandably preoccupied with self-preservation at the time, while many quoted the stoppage of electric clocks as the time of occurrence. Since the tornado caused a simultaneous power failure over a large area, the clocks in this area all stopped at the same time. The most reliable of the times have been entered in boxes in figure 1. They show that the tornado began at about 1815 CST and continued until shortly after 1953 CST for a total duration of a little more than 1 hour and 38 minutes. (The tornado continued for about 3 miles beyond the last time check of 1953 CST. Its exact time of dissipation was not ascertained.)

TABLE 2.—*Speed of movement of the tornado for various time intervals. Speed was determined for only the first 68 miles of the 71-mile path*

		m. p. h.
1815–1836 CST	12 miles in 21 minutes	34.3
1836–1903	18 miles in 27 minutes	40.0
1903–1921	13 miles in 18 minutes	43.3
1921–1953	25 miles in 32 minutes	46.9
Average	68 miles in 98 minutes	41.6

Accuracy of the speed of movement of the tornado is dependent upon the accuracy of the time reports, and can be taken only as a crude approximation for small portions of the path. Calculated speeds for various intervals are given in table 2. The table shows an apparent acceleration of the tornado; however, it must be realized that the time checks are not accurate enough to establish this definitely. For example, the time of first contact with the ground was variously reported in the range from 1815 to 1825 CST, sufficient to alter the initial speed given of 34.3 miles per hour.

Unusual Characteristics

Funnels: Evidence of multiple tornadoes was found in the Williamsburg-Homewood, Kans., area. A number of witnesses reported multiple funnels, with one witness claiming as many as six. Witnesses generally agreed that there was a massive main tornado with other smaller funnels in various stages of formation and dissipation surrounding it. The damage showed at least two paths of destruction in the Williamsburg-Homewood area, although the paths merged for a while into a broader path of destruction west of Homewood. The northernmost path could not be followed beyond the position shown in figure 1, and it is assumed that this tornado dissipated.

Multiple funnels were also reported in the Kansas City area. Some of the tree damage between Ruskin Heights and Knobtown appeared to support the existence of 1 or 2 additional funnels.

Color: From Williamsburg to Ottawa many witnesses stressed the fact that the funnel cloud appeared white in color. This may have been due to the fact that the setting sun to the west provided illumination to the funnel as it approached. Some witnesses reported seeing sunlight beyond the tornado. In the greater Kansas City area witnesses reported a heavy black cloud preceding a gray-white funnel.

Precipitation, lightning, and noise: In the Williamsburg-Ottawa area most witnesses reported only brief rain and a spattering of hail prior to the tornado with none during its passage. Reports of thunder and lightning varied, but many claimed that there was little if any in the tornado cloud itself.

A couple of witnesses reported warming before the tornado occurred; i. e., with the tornado at least a mile away.

The noise of the tornado was described by many witnesses. Generally it was perceptible about 5 minutes before the tornado struck. The sound was described as similar to many locomotives or many jet airplanes. The characteristic sound of the tornado appears to have been one of the most reliable precursors of its approach.

Orientation of debris: In the early portions of the path debris fell generally along the path. Later there was a distinct pattern of contrasting flow. This pattern was best observed at the North Windy crossroads (see fig. 1) where small trees in the right (southern) portion of the path fell in a direction of about 70°, which was along the path, and small trees in the left (northern) portion of the path fell in a direction of about 135°, which was into the path. The trees, typical of the small trees growing along section-line roads in eastern Kansas, showed a change in their direction of fall in a distance of less than 20 feet. The manner in which the trees fell could be interpreted as indicative of rotating motion or inflow motion. Coupled with the translational speed of the tornado, this information could with certain assumptions be used to compute the rotational and/or inflow speed of the tornado. These computations have not been made, but it may be pointed out that the orientation of debris suggests that translational velocity is of considerable importance.

Fallout of debris: In the greater Kansas City area there were numerous reports of small debris falling out over the city at a distance of 10 or more miles north of the tornado's path. Much of the debris consisted of small pieces of wood, corn husks, wheat straws, and occasional articles of clothing. This occurrence immediately suggested to the public that a second tornado had passed aloft over the main portion of the city. However, the debris is believed to have originated from the one tornado farther south for the following reasons: (1) The only source of debris was from the one tornado; (2) debris in the tornado was carried to great heights (a jet pilot flying at high altitude in the storm area observed debris rising to a height of 30,000 feet), and (3) winds at 30,000 feet (210°, 90 knots) were quite capable of carrying the debris to the north of the path during fallout.

Dissipation: It was not possible to follow a damage path of the tornado beyond a point 2 miles northeast of Knobtown, Mo. The funnel apparently dissipated by becoming longer and narrower with time before lifting into the cloud and dissipating. Before disappearing the portion in contact with the ground was described as having a whipping motion. One witness reported that the tornado broke up rapidly like a bursting balloon.

Summary

The Kansas-Missouri tornado had a path of considerable length and of considerable width. It was on the ground virtually all of the way during its 71-mile path. Only the fact that most of its path was over rural areas of Kansas prevented it from causing much greater death and destruction.

Acknowledgments

The authors are indebted to Mr. Roderick B. Cupp, manager of radio station KOFO, Ottawa, Kans., for valuable information and assistance; and to the many witnesses who were interrogated and who volunteered information by letter.—*D. T. Williams and Howard H. Hanks, Jr., SELS Center, U. S. Weather Bureau, Kansas City, Mo.*

SOME RADAR ASPECTS OF THE MAY 20, 1957, KANSAS-MISSOURI TORNADO

The large thunderstorm cell with which the Kansas-Missouri tornado of May 20, 1957, was associated was tracked as a distinct echo by Topeka radar (WSR 3) from east of Wichita, Kans., to beyond Kansas City, Mo. By 1700 CST, while the storm was still well to the southwest of Emporia, Kans., it was evident from radar indications that this was a storm of unusual intensity. One aspect of the radar observations of this storm that may be worthy of note was the configuration of the vertical cross section of the echo as shown

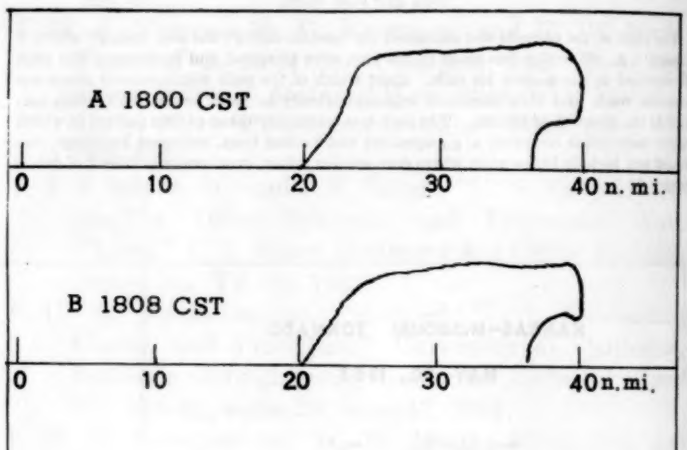

FIGURE 1.—RHI radar echoes of Kansas-Missouri tornado May 20, 1957, as observed at Topeka, Kans.

by the RHI (Range-Height Indicator) scope. By 1800 CST a pronounced anvil-shaped extension from the southern edge of the echo was noted. An appendage then developed at the outer end of the anvil and rather rapidly grew downward to the ground leaving an enclosed clear area between it and the main echo. The time and place where the appendage extended down to the ground as observed by radar were within a few minutes and a few miles of the beginning of the ground path of the tornado as determined by Williams and Hanks (see fig. 1 of their note on p. 205). Following development of the appendage the area of the main echo seemed to shrink in size, but the clear space between the main echo and the appendage was maintained for about 90 minutes.

The five sketches in figure 1 show the appearance of the anvil-shaped echo and the appendage during the time it was under observation. Sketch D is reproduced from a rough drawing made by the radar operator at 1845 CST at about the time the tornado was south of Ottawa, Kans. The other sketches were constructed from memory after the event, so times and details represented in them are only approximate. Photographs of the Topeka radarscope were not obtained.

Figure 1A shows the approximate shape and appearance of the anvil-shaped echo when it was first observed south of Topeka at about 1800 CST. The echo was roughly circular and about 20 nautical miles in diameter with the nearer edge 20 nautical miles from Topeka. The anvil or hammerhead configuration was maintained with little change for 5 to 8 minutes.

Figure 1B shows the approximate shape and size of the echo when the appendage was first observed. The time the appendage was first noted can be fixed as not later than 1810 CST and it was more likely about 1808 CST. The outer edge of the echo was located over Waverly, Kans., at that time. The appendage grew downward rapidly and the radar operator estimates it was about 2 minutes from the time the appendage was first noted until it appeared to reach the ground. The downward growth was rapid enough that it was readily apparent with each vertical sweep on the RHI scope.

Figure 1C shows the approximate configuration of the echo at the time the appendage appeared to reach the ground. The appendage was estimated to be 1½ miles wide and the clear area also 1½ miles wide, with the top of the clear area about 20,000 feet high. Using the 2-minute estimate for downward growth of the appendage gives an approximate time of 1810 CST for the sketch in figure 1C. This determination places the touchdown of the pendant 5 minutes earlier and some 4 or 5 miles southwest of the beginning of the ground path of the tornado 2 miles southwest of Williamsburg as determined by Williams and Hanks in the preceding note. When the radar was returned to PPI (Plan-Position Indicator) scanning at about this time, no out-of-the-ordinary configuration was noted although the operator had been fully expecting to observe the hook shape thought to be associated with tornadoes.

Figure 1D is based upon a rough sketch made at 1845 CST at approximately the time the tornado was south of Ottawa, Kans. In a telephone conversation, the Ottawa cooperative observer some 10 minutes after the time of this sketch reported he heard the tornado but had been unable to see the funnel because of heavy rain, although people in the southern part of Ottawa south of the heavy rain area had seen the funnel. The observer was approximately 3 miles north of the tornado track as determined by Williams and Hanks. By this time the overall size of the rain echo had noticeably decreased. The width of the clear space between the appendage and the main echo was still about 1½ miles, but the height of the clear space had risen from about 20,000 to 30,000 feet. Again the PPI presentation showed no indication of a hook in the tornado area, but a small and rather indefinite hook shape could be detected near the north edge of the main echo. It was at about this time that a pilot reported seeing two funnels touching the ground between Baldwin City and Ottawa. Baldwin City is 11 miles north-northeast of Ottawa.

Figure 1E is the approximate appearance of the RHI presentation at about 1940 CST when the tornado was near the Kansas-Missouri line. By this time the clear space between the appendage and the main echo was becoming indistinct but it was still detectable and appeared to have opened up all the way to the top of the echo.—*Richard A. Garrett and Ralph T. Tice, Weather Bureau Airport Station, Topeka, Kans.*

WORLD RECORD LOW TEMPERATURE

SOUTH POLE, MAY 11, 1957

At 1445 GMT on May 11, 1957, there occurred at the Amundsen-Scott IGY Station (South Pole) the lowest temperature yet observed anywhere on the earth's surface, −100.4° F. Table 1 presents the data at 12-hour intervals during the period May 9–11, with three additional observations on May 11. Included are date, time (GMT), surface pressure (mb.), surface wind direction according to the meridian along which the wind is blowing toward the Pole, windspeed in knots, snow surface temperature (° F.), screen (air) temperature at 2 meters, air temperature at 5 m., and air temperature at 10 m.

TABLE 1.—*Meteorological data, Amundsen-Scott IGY Station (South Pole), May 9–11, 1957*

Date	Time (GMT)	Pressure (mb.)	Wind		Temperature (° F.)			
			Direction (meridian)	Speed (kt.)	Snow	Air 2 m.	Air 5 m.	Air 10 m.
May 9	0000	673.6	110E	11	−93.1	−90.5	−90.4	−88.8
Do	1200	674.1	90E	9	−96.6	−96.0	−96.0	−95.2
May 10	0000	672.6	70E	12	−99.5	−96.5	−96.8	−95.5
Do	1200	672.2	50E	11	−94.5	−92.5	−92.5	−91.9
May 11	0000	674.2	50E	13	−95.0	−92.8	−92.6	−91.1
Do	1200	673.3	40E	10	−99.0	−96.4	−93.9	−88.6
Do	1400	674.9	30E	6	−96.2	−91.5	−90.8	−88.8
Do	1445	----------	50E	4	−101.5	−100.4	−99.0	−92.0
Do	1800	674.9	30E	7	−85.2	−85.6	−85.1	−85.0

TABLE 2.—*Mean and extreme temperatures, Amundsen-Scott IGY Station (South Pole), April, May, June, 1957*

Month 1957	Mean wind		Temperature (° F.)		
	Direction (meridian)	Speed (kt.)	Mean	Maximum	Minimum
April	20E	15	−69.7	−25.6	−89.1
May	30E	15	−68.3	−29.7	−100.4
June	40E	17	−69.5	−42.3	−97.1

The sharp temperature drop from 1400 to 1445 GMT at all levels occurred when the wind speed fell from 6 to 4 knots, and it seems related to a diminution in the vertical mixing of the air rather than to advection of colder air from elsewhere. The great rise in temperature from 1445 to 1800 GMT was associated with a slight increase in windspeed, but the significant factor seems to have been the increased radiation received from a layer of altostratus cloud which moved in to cover half the sky. This layer is estimated, from radiosonde data less than 3 hours previous to the time of appearance, to have had a temperature not lower than −72° F. Ice crystals fell from a cloudless sky throughout the period until 1800 GMT on May 11, when the altostratus layer appeared, and rime ice or "snow down" was observed at 1200 GMT on May 8 on the snow surface and on windward surfaces. At this time the snow surface temperature was −87.4° F., and the air temperature was −85.3° F.

A "cold spell" with temperatures down to −95° F. was experienced for several days prior to the record low temperature. The temperatures had been averaging about 20° F. warmer until then. In general, the surface windspeed has been stronger than first expected, but not strong enough to diminish the very strong surface temperature inversion averaging about 50° F. in the 25- to 30-mb. thick layer just above the snow surface.

As there has been much speculation about the temperatures expected at the South Pole (2,800 m. above m. s. l.), mean and extreme temperatures for the period April–June 1957 are given in table 2.

Further discussion on the aerology and micrometeorology of this event will be found in "Some Aspects of Antarctic Geophysics," by H. Wexler, to be published in a forthcoming issue of *Tellus*.—*E. J. Flowers,* Chief Meteorologist, Amundsen-Scott IGY Station.*

*Mr. Flowers, who submitted the information contained in this note, did not have an opportunity to check the final form of the manuscript.—*Ed.*

THE WEATHER AND CIRCULATION OF JUNE 1957 [1]

Including an Analysis of Hurricane Audrey in Relation to the Mean Circulation

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1. COMPARISON WITH SPRING MONTHS

The weather in the United States during the spring of 1957 was severe in many areas. The prolonged drought of 1952–56 in southern and central parts of the Great Plains [16] was broken by blizzards and heavy rains during both March [4] and April [1]. Intensification of the heavy precipitation during May [3] produced disastrous floods in this region. At the same time, tornado activity, which had been frequent in April, reached peak intensity and made this May the worst tornado month ever experienced in the United States.

In many respects June's weather regime was a continuation of that which had prevailed throughout the spring season. This is well illustrated by figure 1, which shows that the pattern of departure of average temperature from normal during June closely resembled the corresponding average for the months of March, April, and May. Some similarity was also apparent between the maps showing the percentage of normal precipitation for June and for the preceding three months. (See *Weekly Weather and Crop Bulletin, National Summary* for weeks ending June 10 and July 8). During June, tornadoes, heavy rains, and floods in central portions of the United States again made newspaper headlines.

On a month-to-month basis the weather in the United States was also unusually persistent. The striking resemblance between April and May of 1957 was noted in the previous article of this series [3]. Between May and June of this year, only 18 out of 100 stations scattered over the United States had changes of more than one class in their monthly mean temperature anomaly, compared to an average of 30 for the years from 1942 to 1954 [10] and 40 expected by chance. No change in precipitation class was reported by 42 stations, a considerably greater number than the 33 expected both by chance and by the average of previous May–June periods.

Although many features of June's weather were thus quite persistent from the preceding month and season, nevertheless there were some large changes. Most striking, perhaps, was the warming which occurred in the Southwest (fig. 1), where some stations reported a four-class change in temperature, from much below normal during May to much above normal in June. This warming

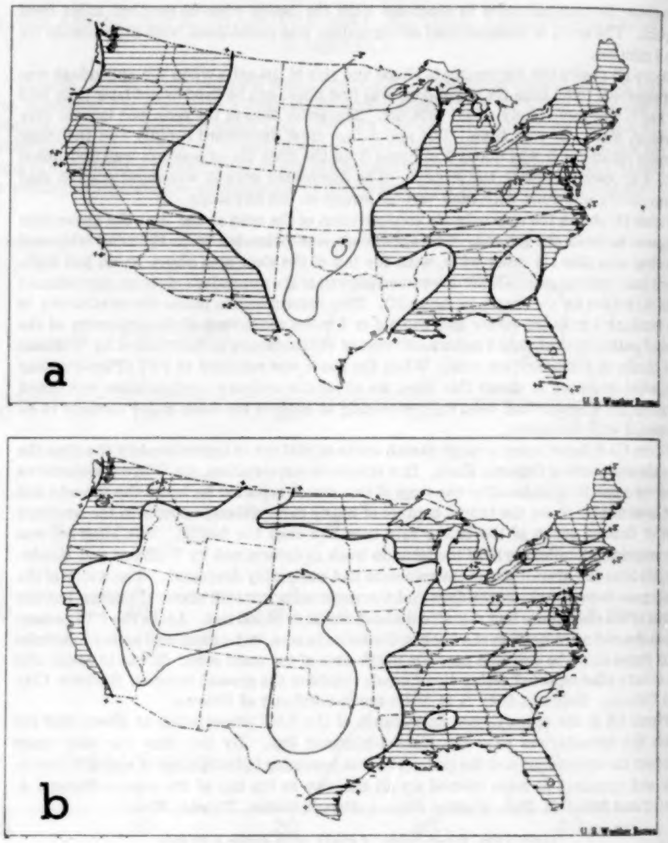

FIGURE 1.—Departure of average surface temperature from normal (° F.) with shaded areas normal or above, for (a) June 1957 and (b) spring 1957 (March, April, May). Similarity in pattern is striking except for warming in the Southwest in June. (From *Weekly Weather and Crop Bulletin, National Summary* for weeks ending June 10 and July 1, 1957.)

was associated in part with an abrupt northward shift of the mean jet stream at the 200-mb. level as illustrated in figure 2, which gives the location of the jet axis computed from a series of monthly mean 200-mb. maps. Whereas the mean jet was located over northern Mexico and southern Texas during the three spring months, it traversed the central Plateau and Northern Plains during June (fig. 3). This shift was probably greater in magnitude than the normal seasonal trend, but normal 200-mb. maps are not available for comparison. At any rate, it was reflected in displacement of the area of worst weather

[1] See Charts I–XVII following p. 228 for analyzed climatological data for the month.

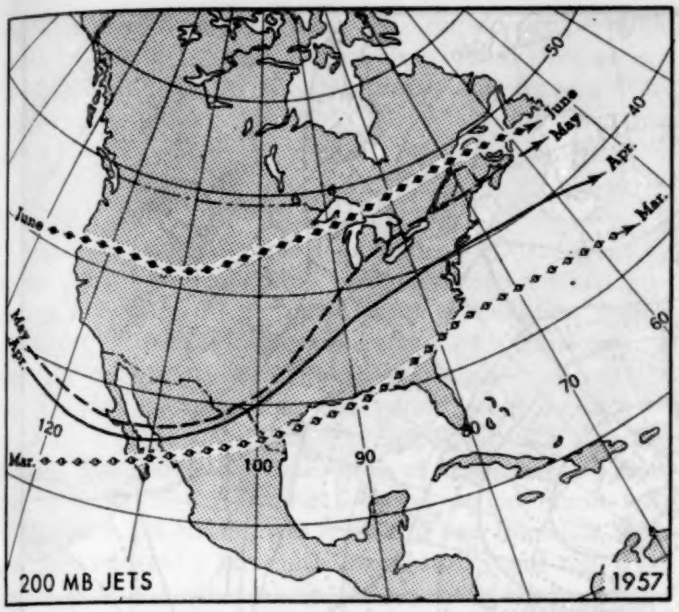

FIGURE 2.—Location of principal axis of mean jet stream during each spring month of 1957, as obtained from monthly mean 200-mb. charts. Gradual northward progression over the 4-month period of the jet in the East contrasted with its abrupt northward shift from May to June in the West.

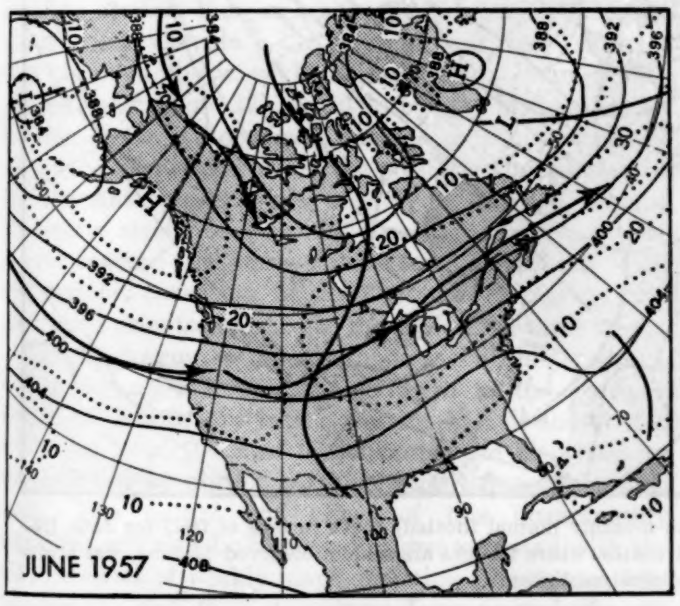

FIGURE 3.—Mean 200-mb. contours (solid, in hundreds of feet) and isotachs (dotted, in meters per second) for June 1957. Solid arrows indicate the position of the 200-mb. mean jet stream. Note split jet around blocking High in Gulf of Alaska, with one branch between 40° N. and 50° N. and the other around 70° N.

(tornadoes and floods) from the Southern Plains during May to northern portions of the Plains and Mississippi Valley in June. The northward shift of the jet stream occurred also in the eastern part of the country, but to a lesser degree and in a more gradual fashion (fig. 2). There too it was accompanied by general surface warming, with parts of the Northeast changing from below normal temperatures in May to above normal in June.

Thus, June 1957 was a transition month in which the weather and circulation pattern of spring was replaced by one more typical of summer. This evolution is examined on a week-to-week basis in section 3, after details of the monthly mean are discussed in section 2. The establishment of a summer regime culminated, during the last week of the month, with the appearance of hurricane Audrey. This storm is analyzed in relation to the mean circulation in section 4.

2. MONTHLY MEAN CIRCULATION AND WEATHER

The general circulation over North America during June 1957 was fairly simple in pattern, consisting of a deep trough through the central part of the continent flanked by ridges along each coast. This pattern is well illustrated by the monthly mean maps at 200 mb. (fig. 3) and 700 mb. (fig. 4), and it was evident at all levels of the atmosphere from sea level (Chart XI) up to 100 mb. (Chart XVII). The northern portion of each ridge was affiliated with a blocking High. These Highs, centered over Greenland and Alaska, respectively, were of the warm type since they extended as closed circulations up to the 200-mb. level. Warmth, relative to its surroundings, was also a feature of the southern portion of the North American trough extending through the western Gulf of Mexico, since a closed Low was present at 700 mb. (fig. 4) but no trough at all at 200 mb. (fig. 3). This trough was made up in part by tropical activity, especially hurricane Audrey (see sec. 4).

The dotted lines in figure 4 show that monthly mean 700-mb. heights were below the June normal throughout the length of the trough from Central America to the Arctic Ocean, with greatest departures (−210 ft.) over northern Manitoba. Conversely, above normal heights prevailed in the mean ridges along the Atlantic and Pacific coasts. The pattern of surface temperature departure from normal for the month was very similar to this, as illustrated in figure 1A and Chart I–B for the United States. As would be expected, however, the axes of above and below normal temperatures were displaced westward (about 5° longitude) relative to the corresponding values for height, with warm air in the southerly flow east of the trough and cool air in the northerly components to its west. Maximum temperature anomalies in the United States were +4° F. in southern New England and western California, where positive 700-mb. height anomalies are centered in figure 1, and −4° F. around Duluth and Oklahoma City.

The mean trough through the central United States was associated with the passage of numerous migratory cyclones (Chart X) and with the influx of considerable moisture from the Gulf of Mexico at low levels. As a result abundant precipitation was widespread throughout the United States (Charts II and III). Rainfall was especially heavy in the region of stronger than normal

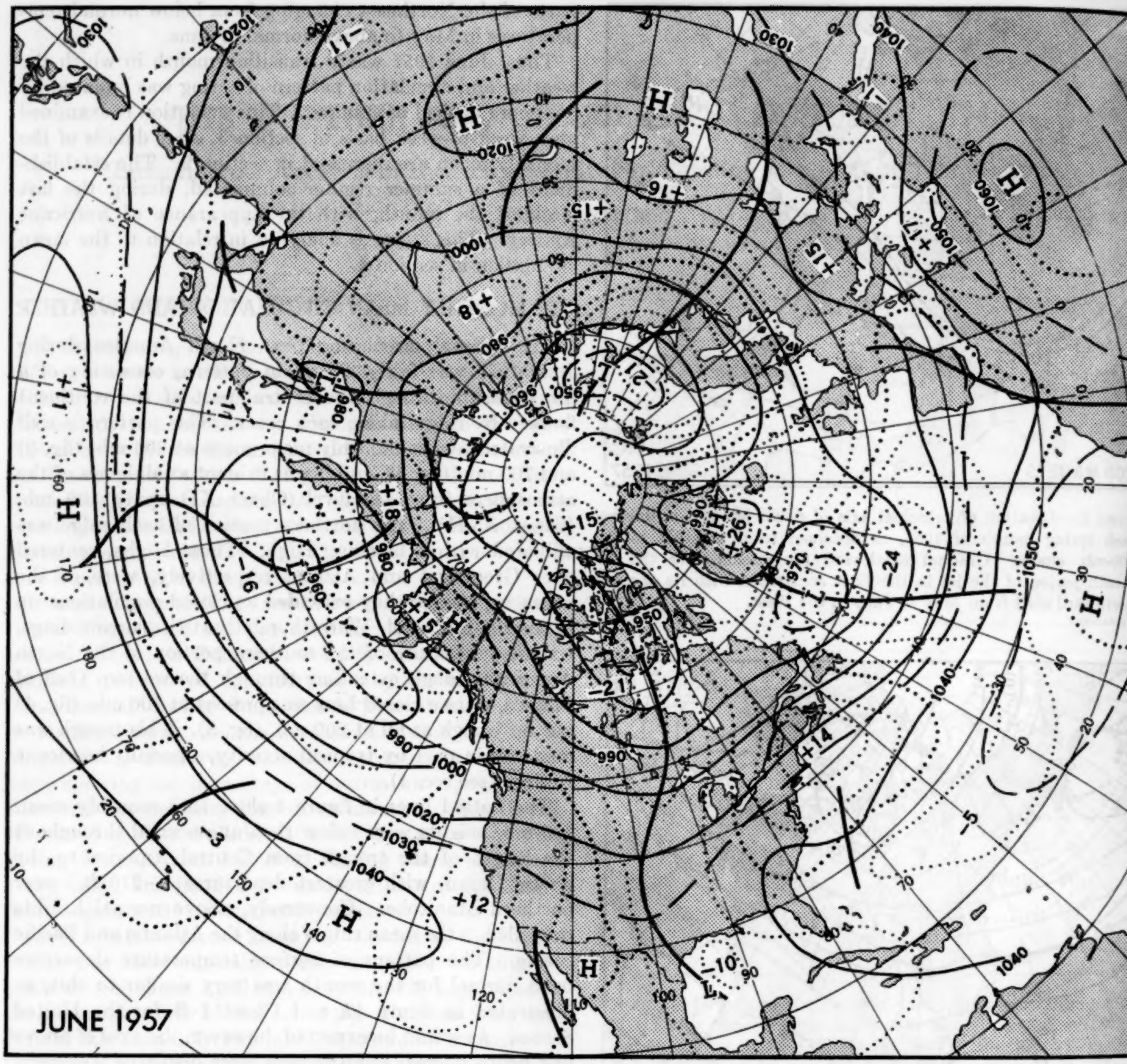

FIGURE 4.—Mean 700-mb. contours (solid) and height departures from monthly normal (dotted) (both in tens of feet) for June 1957. The mean trough (heavy vertical line) through the central United States, where troughs are seldom observed in June, was accompanied by severe weather in many parts of the Great Plains and Mississippi Valley.

southerly winds just east of the trough, and over twice the normal amount fell in portions of the Central Plains, Mississippi Valley, and Great Lakes area. This was in good agreement with the results of an earlier study on the relation between summer rain in this region and monthly mean 700-mb. charts [5]. The intensity and areal extent of this rainfall is indicated by the fact that this was the wettest June on record at Shreveport, La., St. Louis, Mo., Sioux City, Iowa, Fort Wayne, Ind., Youngstown, Ohio, and Erie, Pa.

In contrast to the heavy rains in other parts of the country, the dry weather of April [1] and May [3] continued along the Atlantic seaboard from Virginia northward. This was the third driest June in 84 years at New Haven, Conn., and the second driest at Providence, R. I. At the latter city only 1.58 inches of rain fell from April 10 to June 30, the most prolonged spring drought in 53 years of record. This 3-month dry spell was closely related to the persistence of a mean ridge and its accompanying center of positive height anomaly over the North Atlantic States each month from April through June (see monthly mean 700-mb. charts in fig. 4 and in the previous

two articles of this series [1 and 3]). Subsidence prevailed under this ridge, with anticyclonic conditions at sea level (Chart XI), as the Northeast was traversed by numerous migratory Highs (Chart IX) but very few Lows (Chart X).

3. TRANSITION WITHIN THE MONTH

The abrupt northward displacement of the monthly mean jet stream from May to June illustrated in figure 2 was accomplished by an interesting evolution within the month of June. This was investigated by constructing isotachs on a sequence of 5-day mean 200-mb. charts a week apart encompassing the period from June 1 to July 3. The location of the principal jet axis over the United States obtained from each of these maps is illustrated in figure 5. During the first period (June 1–5) the 200-mb. jet stream was split into two branches, with one axis unusually far south over Mexico and the West Indies, and the other along the northern border of the United States. The next week (June 8–12) each of these branches migrated northward, the first to the Southern Plains and the second to southern Canada. By the third period (June 15–19) the two jet axes apparently merged, and a single well-developed jet stream (with geostrophic speeds of 70–80 m. p. h.) curved cyclonically from the Central Plateau across the Northern Plains into southeastern Canada. Its position was very close to that given on the monthly mean 200-mb. map (fig. 3). A week later (June 22–26), little change in intensity or location of the jet occurred, except for some continued northward displacement in the western United States. By the final week (June 29–July 3) a single, intense jet stream stretched across the northern border of the United States. Its anticyclonic curvature in the West and cyclonic curvature in the East was in marked contrast to its orientation during the preceding three weeks.

Thus, in the course of a month, an axis of the jet stream seemed to migrate from the southern to the northern border of the country in the western half of the United States, while in the East initial northward displacement was followed by abrupt southward shift during the final week. The nature and effect of this intramonthly transition will now be discussed in greater detail with the aid of a series of weekly maps depicting 5-day mean 700-mb. heights and their departures from normal (fig. 6), weekly surface temperature anomalies (fig. 7), and total weekly precipitation (fig. 8).

FIRST WEEK

The split in the jet stream during the first two periods given in figure 5 was reflected as a sheared trough at 700 mb. from June 4 to 8 (fig. 6A), with one low center over Texas and another over Labrador. Each of these Lows was associated with an area of below normal heights at 700 mb. (fig. 6A) and below normal temperatures at the surface (fig. 7a). Weekly temperature departures averaged as much as −6° F. in central Texas and in parts

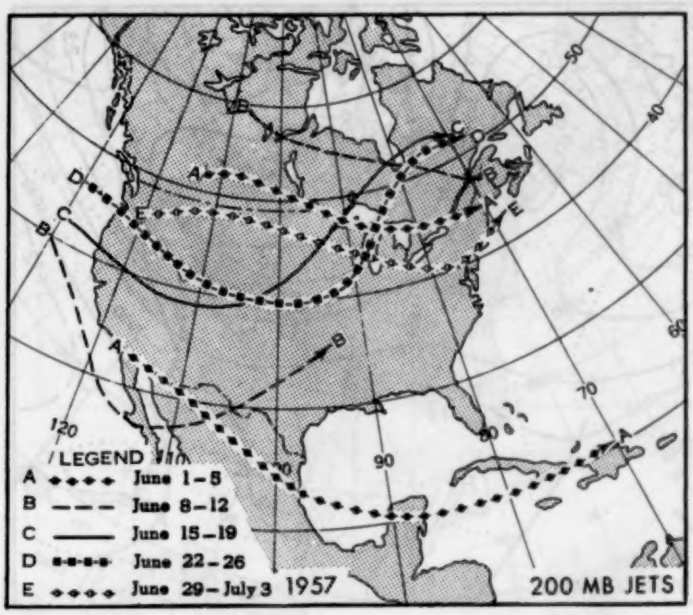

FIGURE 5.—Location of axis of mean jet stream during selected periods of June 1957, as obtained from a series of 5-day mean 200-mb. maps one week apart. The jet stream was split into two branches during the first two periods (A and B). During the remainder of the month (C, D, E) a single well-developed jet shifted progressively northward in the West and southward in the East.

of the Northeast. In the latter region a cold Canadian airmass carried by the stronger than normal northwesterly flow shown in figure 6A, dropped temperatures to record low levels at the end of the week. Hartford, Conn., recorded 38° F. on the 10th, the lowest June temperature ever observed there.

Over most remaining areas of the Nation both 700-mb. heights and surface temperatures averaged above normal. The strong ridge in the West was accompanied by temperatures over 6° F. above normal in most of the Plateau and Rocky Mountain regions. Daytime temperatures in the 90's caused rapid snowmelt in the mountains, resulting in floods along several rivers in Colorado.

The only significant precipitation in the United States during the first week of June occurred in southeastern and south-central portions of the country in connection with the upper Low over Texas and the moist southerly flow to its east. Locally heavy showers, ranging up to 6 inches on June 1 at Madill, Okla., aggravated the serious flood problem of May [3] in the Southern Plains and lower Mississippi Valley. Additional flooding was reported on the Red and Arkansas Rivers and their tributaries in portions of Texas, Oklahoma, Arkansas, and Louisiana. Another area of heavy rainfall, totaling from 2 to 6 inches, occurred in the Middle and South Atlantic States as a result of the passage of two cyclones. The first of these storms developed as a wave on the polar front in southern Virginia on June 5. The second was tropical in origin, forming in the eastern Gulf of Mexico on June 8. The

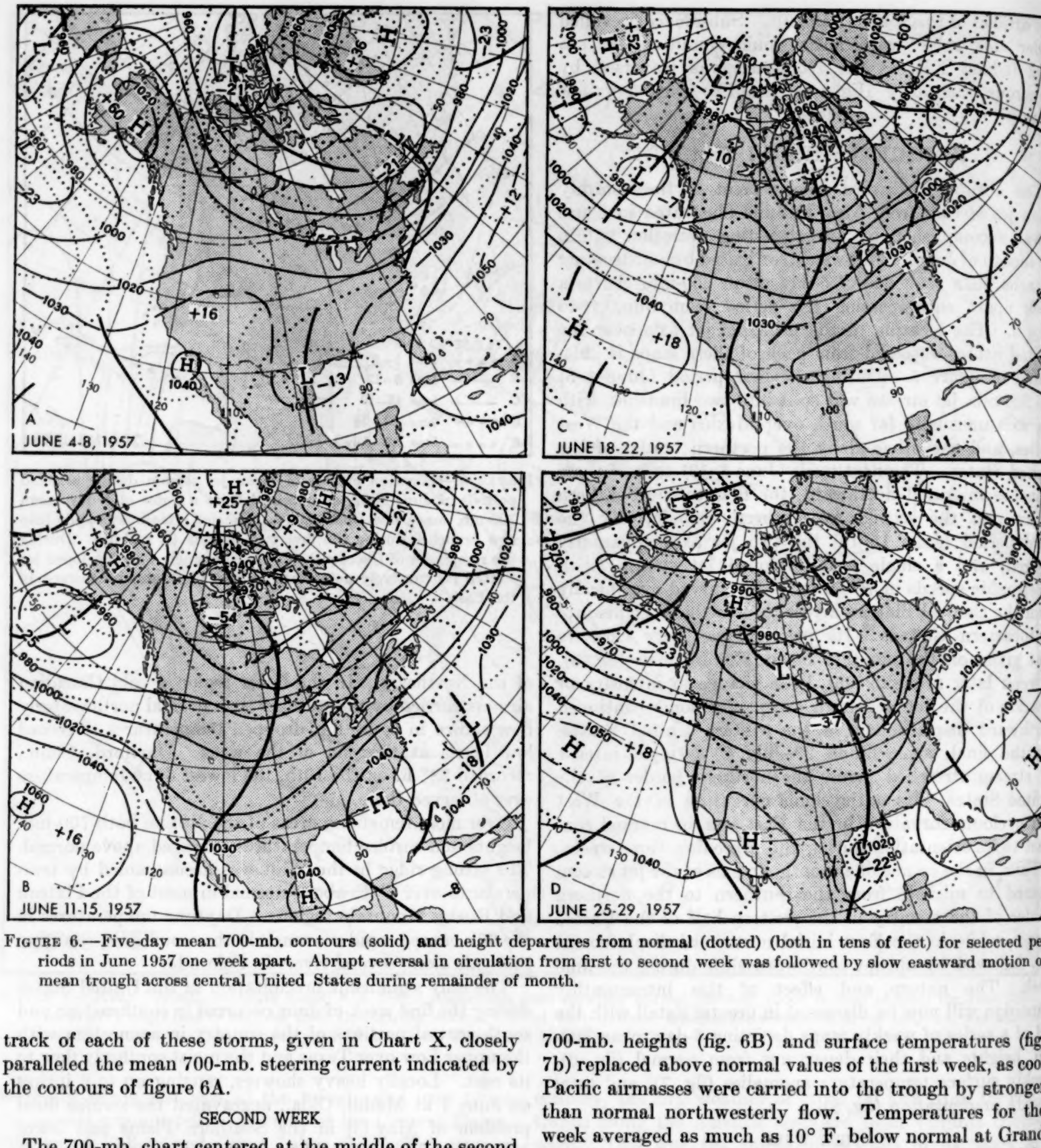

FIGURE 6.—Five-day mean 700-mb. contours (solid) and height departures from normal (dotted) (both in tens of feet) for selected periods in June 1957 one week apart. Abrupt reversal in circulation from first to second week was followed by slow eastward motion of mean trough across central United States during remainder of month.

track of each of these storms, given in Chart X, closely paralleled the mean 700-mb. steering current indicated by the contours of figure 6A.

SECOND WEEK

The 700-mb. chart centered at the middle of the second week of June (fig. 6B) was quite different from the map for the first week (fig. 6A). Most of North America was now under the influence of a deep full-latitude trough extending from the Arctic Ocean through central Canada and the Great Plains of the United States into the Pacific Ocean off the coast of Mexico. A single, intense jet stream flowed around this trough at the 200-mb. level (fig. 5C). In the western half of the United States below normal 700-mb. heights (fig. 6B) and surface temperatures (fig. 7b) replaced above normal values of the first week, as cool Pacific airmasses were carried into the trough by stronger than normal northwesterly flow. Temperatures for the week averaged as much as 10° F. below normal at Grand Junction, Colo., while freezing weather was observed in parts of the Great Basin and central Rockies.

Precipitation was widespread in the cyclonic circulation over the normally arid southwestern quarter of the Nation, with amounts up to 2 inches in southeastern Utah (fig. 8b). Most of this rain (and some snow) was associated with the slow eastward motion of a complex surface and upper-level Low which developed in Nevada on the 9th

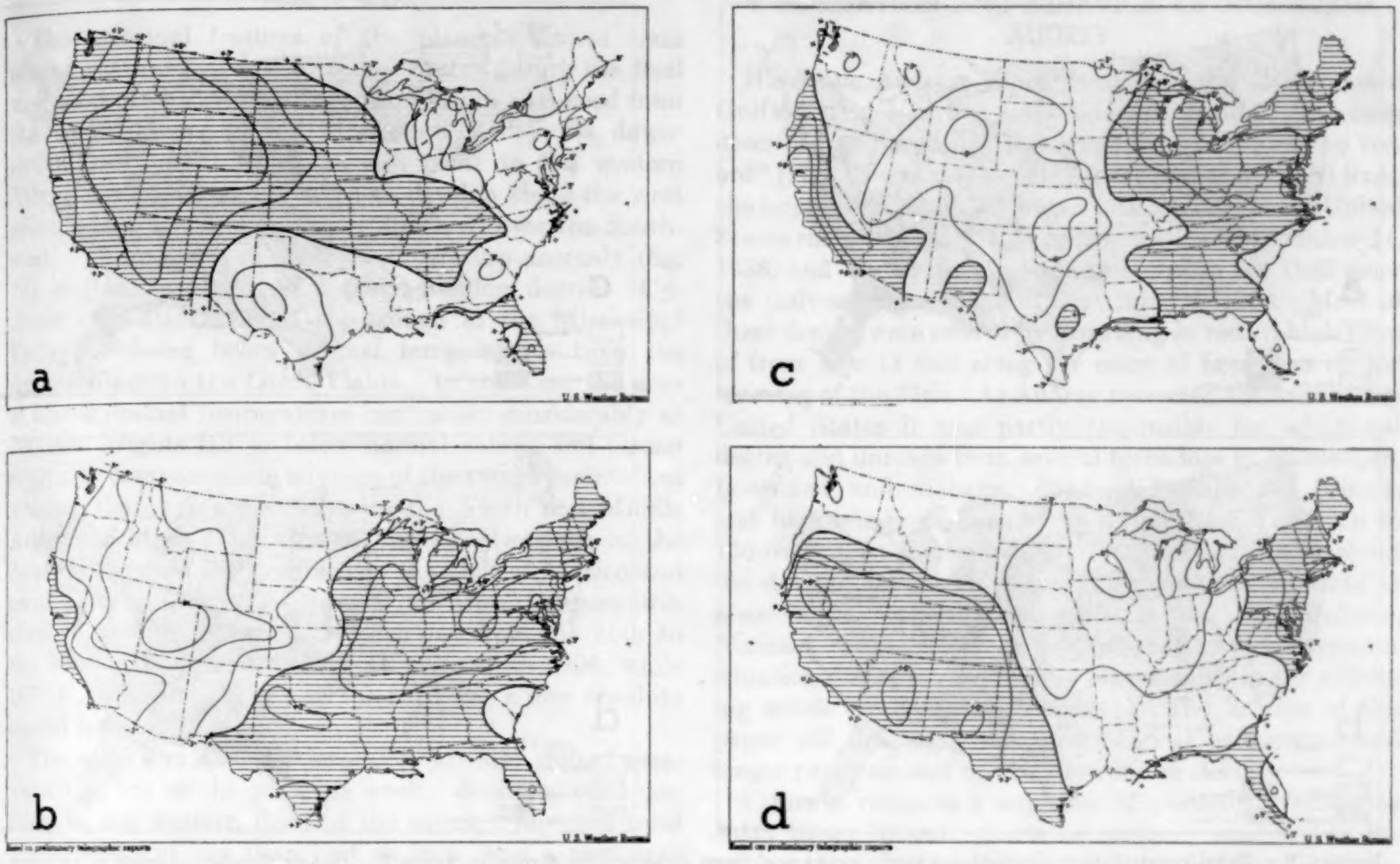

FIGURE 7.—Departure of average surface temperature from normal (° F.) for weeks in June 1957 centered on the 5-day mean periods shown in figure 6. Progressive eastward motion of pattern was apparent during last 3 weeks. (From *Weekly Weather and Crop Bulletin, National Summary,* for weeks ending (a) June 10, (b) June 17, (c) June 24, and (d) July 1.)

and dissipated in the Central Plains on the 12th (Chart X). It is noteworthy that most of the month's above normal precipitation in the Southwest (Chart III) fell during this second week.

Precipitation (fig. 8b) was also generally heavy in the moist southerly current east of the 700-mb. trough [5]. On the 14th and 15th a strong cold front separating cool Pacific from warm Gulf air became quasi-stationary in the upper Mississippi Valley. Excessive rains (up to 18 inches), accompanied by flash floods, fell in St. Louis and surrounding areas of Missouri and Illinois, and a tornado occurred in Springfield, Ill. As this front was carried northward by strong southerly winds in advance of an upper-level Low over the Rockies, heavy rains on the 16th and 17th caused serious flooding in parts of Kansas, South Dakota, and Minnesota. In the latter State, new 24-hour rainfall records of from 7 to 9 inches were established at a number of communities.

On the other hand, rains in Texas were neither as frequent nor as extreme as they had been in previous weeks, and the State received much-needed hot sunny weather in the latter part of the week. This desiccation was produced by the foehn effect in stronger than normal westerly components at 700 mb. (fig. 6B), and was related to the northward shift of the 200-mb. jet stream shown in figure 5.

The circulation in the eastern third of the United States was dominated by a strong ridge at 700 mb. (fig. 6B), with high center over northwestern Florida and center of above normal heights over New England. Above normal temperatures prevailed in and west of this ridge, with maximum departures for the week of more than 6° F. in the Northeast (fig. 7b). On the 16th, the mercury reached 100° F. in Philadelphia, setting a new record for the date, while at Burlington, Vt., 96° F. equaled the highest ever observed there in June. The persistence of anticyclonic circulation over the East inhibited the formation of precipitation, and less than half an inch of rain fell during the week along the entire Atlantic coast except for southern Florida and northern Maine (fig. 8b). The heat and continued lack of rain intensified the drought in southern New England.

THIRD WEEK

Little change occurred from the second to the third week in either the general circulation over North America (fig. 6C) or the patterns of temperature (fig. 7c) and precipitation (fig. 8c) over the United States. The trough in the United States sheared, with the main part moving slowly eastward across the Great Plains. The mean ridge along the east coast intensified somewhat as the center of the subtropical

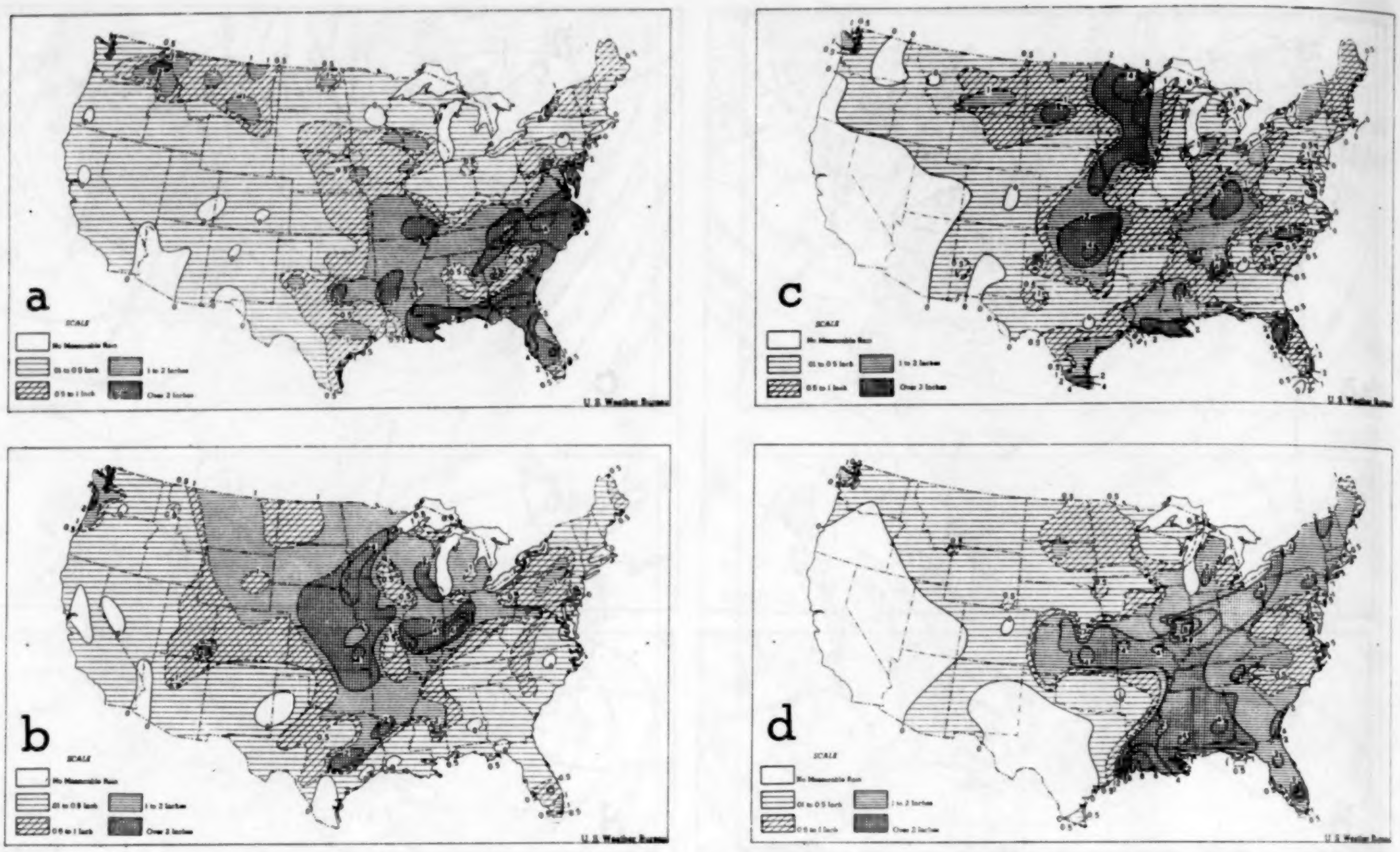

FIGURE 8.—Total precipitation (inches) for same weeks and from same source shown in figure 7. Heavy flood-producing rains (over 4 inches) fell in parts of the Great Plains and Mississippi Valley during each of the last 3 weeks of the month.

High moved northward from the Gulf coast into the South Atlantic States. The ridge along the west coast also strengthened, and a nose of the eastern Pacific High protruded into the southwestern United States where heights rose from below to above normal values.

The weakening of cyclonic circulation in the Southwest (fig. 6C) and the northward displacement of the jet stream (fig. 5) were accompanied by marked surface warming and drying. Temperatures for the week averaged more than 6° F. above normal in western California (fig. 7c), while practically no rain fell in the southwestern quarter of the Nation (fig. 8c). New record high temperatures for June were reported by San Diego, Calif., on the 18th (97.2° F.) and by Yuma, Ariz., on the 24th (120° F.). Several forest fires occurred in southern California, and fire hazard spread over the northern part of the State.

Hot dry weather also highlighted the week in the Northeast, where a persistent center of positive height anomaly (+170 ft., fig. 6C) remained quasi-stationary. For the second successive week, temperatures averaged about 6° F. above normal over a wide area from the Middle Atlantic States to New England and the Great Lakes. At Washington, D. C., the mercury reached 90° F. or above on eight consecutive days from June 12 to June 19. When the heat wave was broken by passage of a cold front from the west on the 19th and 20th, violent thunderstorms occurred in New England, with waterspouts and a tornado reported from New Hampshire. However, little or nor rain fell in coastal areas from Cape Cod to the Carolinas, and parts of New Jersey and southern New England were becoming critically dry.

Most of the remainder of the Nation experienced cool wet weather under the domination of the mean trough in the central United States. Rainfall was again heaviest just east of the trough, with more than 2 inches falling in a narrow band from Oklahoma north-northwestward to the Canadian border (fig. 8c). At Sioux Falls, S. Dak., a new 24-hour precipitation record was established when 4.33 inches fell on the 16th and 17th, causing serious floods on the Big Sioux River. Additional flooding occurred in portions of Minnesota, Kansas, Nebraska, Iowa, Wisconsin, and Oklahoma. One of the most notable storms of the week was a tornado in Fargo, N. Dak., on June 20. It is noteworthy that most of the severe local storms and heavy rains were observed in the vicinity of the 200-mb. jet stream, in the region where the axis curved cyclonically sharply northward (fig. 5, C and D). The week was unseasonably cool in the Great Plains, where temperatures averaged as much as 6° F. below normal. Damaging frost was reported in parts of Colorado, Oregon, and Nevada, while Topeka, Kans., had a record low of 52° F. on the 24th.

FOURTH WEEK

The principal features of the planetary wave train moved eastward over the United States during the final week of June (fig. 6D). The mean trough advanced from the Great Plains to the Mississippi Valley, its downstream ridge went from the east coast to the western Atlantic, a new trough started to develop along the west coast, and a strong high center appeared over the Southwest. The pattern of weekly temperature anomaly (fig. 7d) shifted eastward to a corresponding degree. Cyclonic circulation around the trough in the Mississippi Valley produced below normal temperatures from the Appalachians to the Great Plains. In the East the area of above normal temperatures contracted considerably as 700-mb. heights fell to below normal values, but strong southerly components in advance of the trough maintained warmer than average weather in the North and Middle Atlantic States. The area of abnormal warmth in the Southwest expanded eastward to the Gulf of Mexico and northward to Idaho. At Roswell, N. Mex., temperatures climbed to 105° F. or higher each day from the 25th to the 30th in the worst June heat wave since 1896, while 107° F. in El Paso, Tex., on the 28th was a new absolute record for that station.

The week's rainfall pattern (fig. 8d) also shifted eastward relative to the previous week. Practically all districts in the western third of the country reported total precipitation of less than half an inch, and a vast area from southern Texas northwestward to Oregon had no rain at all. This dry regime was the result of anticyclonic circulation at 700 mb. (fig. 6D) and northward shift of both the jet stream at 200 mb. (fig. 5) and the principal cyclone track at sea level (Chart X).

Except for continuing drought along the Atlantic coast from Cape Cod to Hatteras, nearly all sections of the country east of the Great Plains experienced abundant rainfall, generally in excess of one-half inch. Most of this rain fell in the cyclonic circulation around the mean trough in the Mississippi Valley or in the southerly flow to its east. The greatest amounts, over 2 inches, were observed in two separate zones which merged over the Ohio Valley. From here one band extended west-southwestward into Kansas, the other south-southwestward to the Gulf coast. The first belt of heavy rain was primarily frontal in nature, occurring along a slow-moving cold front from the 26th to the 28th. Rainfall totaled as much as 5 inches in Kansas, 7 inches in Missouri and Indiana, and 11 inches in Illinois. Severe flooding of farmland resulted in these States. The second belt of heavy rain paralleled the path of hurricane Audrey from the Texas-Louisiana border to western New York. Since this hurricane was undoubtedly the weather highlight of the week, and probably of the month, it is discussed separately in the next section.

4. FORMATION AND BEHAVIOR OF HURRICANE AUDREY

Hurricane Audrey, which formed in the southwestern Gulf of Mexico in the early hours of June 25, has been described as "probably the worst June hurricane on record" [17]. It was responsible for the loss of over 500 lives, the largest death toll attributed to any storm in the United States since the New England hurricane of September 21, 1938, and the largest due to any storm in the Gulf since the Galveston hurricane of September 8, 1900. Most of these deaths were caused by drowning in record high tides of from 9 to 11 feet along the coast of Louisiana on the morning of the 27th. As Audrey traversed the continental United States it was partly responsible for additional deaths and damage from several tornadoes in Mississippi, Louisiana, and Alabama; floods in Indiana and Illinois; and high winds in Pennsylvania and New York (up to 100 m. p. h. in Jamestown, N. Y.). Further details about the destruction caused by this hurricane can be found in a special issue of the *Weekly Weather and Crop Bulletin, National Summary* [17]. A detailed analysis of the synoptic situation during its life history is contained in the adjoining article by Ross and Blum [14]. The balance of this paper will deal with the climatological background and longer range aspects of this destructive storm.

Figure 9 contains a sequence of partially overlapping 5-day mean 700-mb. charts as routinely analyzed in the preparation of extended forecasts on Sunday, Tuesday, and Thursday of each week. The series starts with the period from June 15 to 19 (fig. 9A), when the subtropical high center in the eastern United States, which had started to develop during the second week of June (fig. 6B), attained maximum intensity (10,590 ft.) and farthest northward displacement (West Virginia). To its south a broad stream of easterlies occupied the entire Caribbean and Gulf of Mexico. Three days later (fig. 9B) this easterly current acquired more cyclonic curvature as the High weakened somewhat (10,500 ft.) and retreated southward to the Carolinas. By the next map of the series (fig. 9C), a distinct easterly wave had developed in the Gulf of Mexico, while the High remained unchanged over the Carolinas.

Meanwhile the deep polar trough (in the westerlies) which had developed in the Great Plains and southwestern United States during the second week of June (fig. 6B) was moving slowly eastward across the central United States (fig. 9 A, B, C). By the period June 22–26 (fig. 9D) it was located directly north of the easterly wave in the Gulf of Mexico, and a single trough extended southward near the 95th meridian from Minnesota to Central America. According to Cressman [2], such latitudinal superposition frequently produces intensification of both disturbances. In accordance with this hypothesis, a weak closed Low with central height of 10,300 feet formed within the easterly wave in the Gulf (fig. 9D). It was in

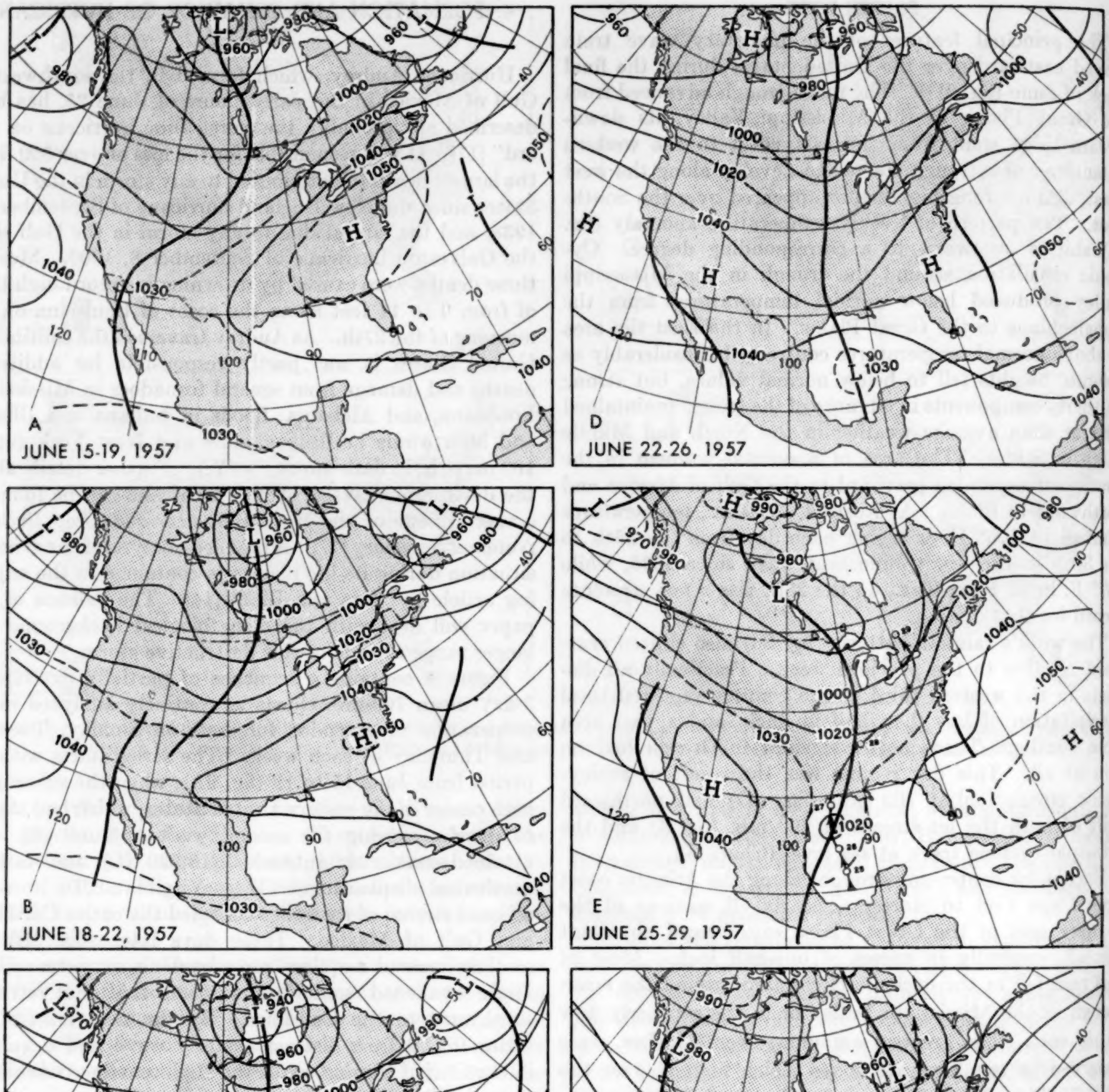

FIGURE 9.—Thrice-weekly, 5-day mean 700-mb. maps (in tens of feet) showing sequence of events prior to and during life history of hurricane Audrey. Track of the hurricane at sea level is shown by the arrows in E for the period June 25–29 and in F for the period June 27–July 1, with position at 1200 GMT indicated by open circles and date along trajectory. During both periods the storm moved sharply northward along the axis of the mean trough.

this Low that Audrey developed, reaching hurricane intensity on the 25th. Its subsequent trajectory across the Gulf of Mexico, United States, and Canada is given by the arrows in the last two maps of the sequence (fig. 9E, F). As Audrey moved northward it entered the westerlies, appearing as a 10,200-foot Low at the southern end of the polar trough on the map for June 25–29 (fig. 9E), and merging with the polar Low near James Bay from June 27 to July 1 (fig. 9F).

The evolution portrayed in figure 9 is illustrated in a somewhat different fashion in figure 10. This chart gives the tracks of the two centers of 5-day mean negative height departure from normal corresponding to the easterly wave and polar trough depicted in figure 9. Figure 10 shows that a negative anomaly first appeared as a weak center (−80 ft.) in the western Caribbean during the 5-day period June 11–15. It subsequently meandered slowly westward across Central America with little change in intensity until it entered the western Gulf of Mexico as a more pronounced center (−140 ft.) during the period June 22–26, when it corresponded to the closed Low shown in figure 9D. Meanwhile the center of below normal heights in the polar trough had been moving slowly eastward across the northern border States. This center apparently merged with or absorbed the tropical center when Audrey accelerated sharply northward (around June 29), so that only a single intense center of negative anomaly (as much as −420 ft.) in eastern Ontario was evident on the maps for June 27 to July 1 and June 29 to July 3.

One of the most significant aspects of figure 10 is the fact that a center of negative height anomaly ultimately associated with hurricane Audrey could be located and traced as a distinct entity on every 5-day mean map starting as early as the period centered June 13. No other single feature of daily or mean maps could be followed by the author with equal facility for so long a period prior to hurricane formation. The quasi-conservative nature of this height anomaly may warrant further research along these lines for other hurricanes.

Another factor investigated in connection with the development of hurricane Audrey was sea surface temperature, since Palmén [11] concluded that hurricanes can be formed only in oceanic regions outside the vicinity of the Equator where the surface water has a temperature above 78°–81° F. All ship observations of water temperature plotted on twice-daily synoptic charts during June were therefore tabulated for the 5° squares delineated in figure 11. The mean temperatures were computed by 10-day periods (and for the entire month) and plotted in the center of each square. These means were then compared with the long period (1887–1936) averages given by Riehl [13]. The departures from this "normal" are given in figure 11, along with the number of observations in each box. It is apparent that, throughout the month, the sea surface was warmer than both the critical temperature of 81° F. and the long-period average in practically all portions of the Caribbean and Gulf of Mexico. It is particularly noteworthy that in the square where Audrey developed, indicated by a hurricane symbol in figure 11C, temperatures rose steadily during the month to a maximum of 85° F., 3° above normal, during the period June 21–30. Although this value is based upon only three observations, it is substantiated by the temperature of 84° F. in adjacent squares to the north and east, where a large number of observations were available.

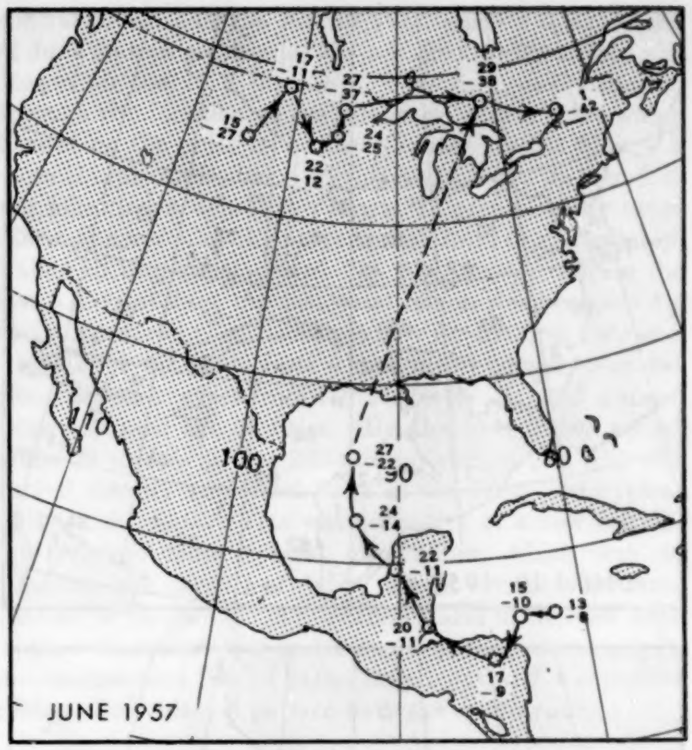

Figure 10.—Tracks of two centers of negative height anomaly from a series of overlapping 5-day mean 700-mb. height departure from normal maps (prepared three times a week) from June 13 to July 1, 1957. Beside each open circle, indicating the location of the anomaly center at map time, is plotted the date of the middle day of the period (above) and the central intensity in tens of feet (below). Trajectory is dashed in region of uncertain continuity. Note that the negative anomaly subsequently associated with hurricane Audrey can be traced back as far as the period June 11–15, 1957.

It has been indicated that both the 700-mb. circulation and the surface water temperatures were favorable for the development of hurricane Audrey. The 200-mb. circulation was considered next since it is well known that strong outflow is required at high levels above a tropical depression before it can intensify to hurricane strength. According to Riehl [12], such divergence is most likely to occur when the storm lies under northerly flow east of an upper (200-mb.) High, where the curvature of the high-level flow is anticyclonic or changes from cyclonic to anticyclonic. In a more recent paper [15] he adds that "For extreme deepening the anticyclone above the hurricane should also be part of a ridge of the long wave pattern in

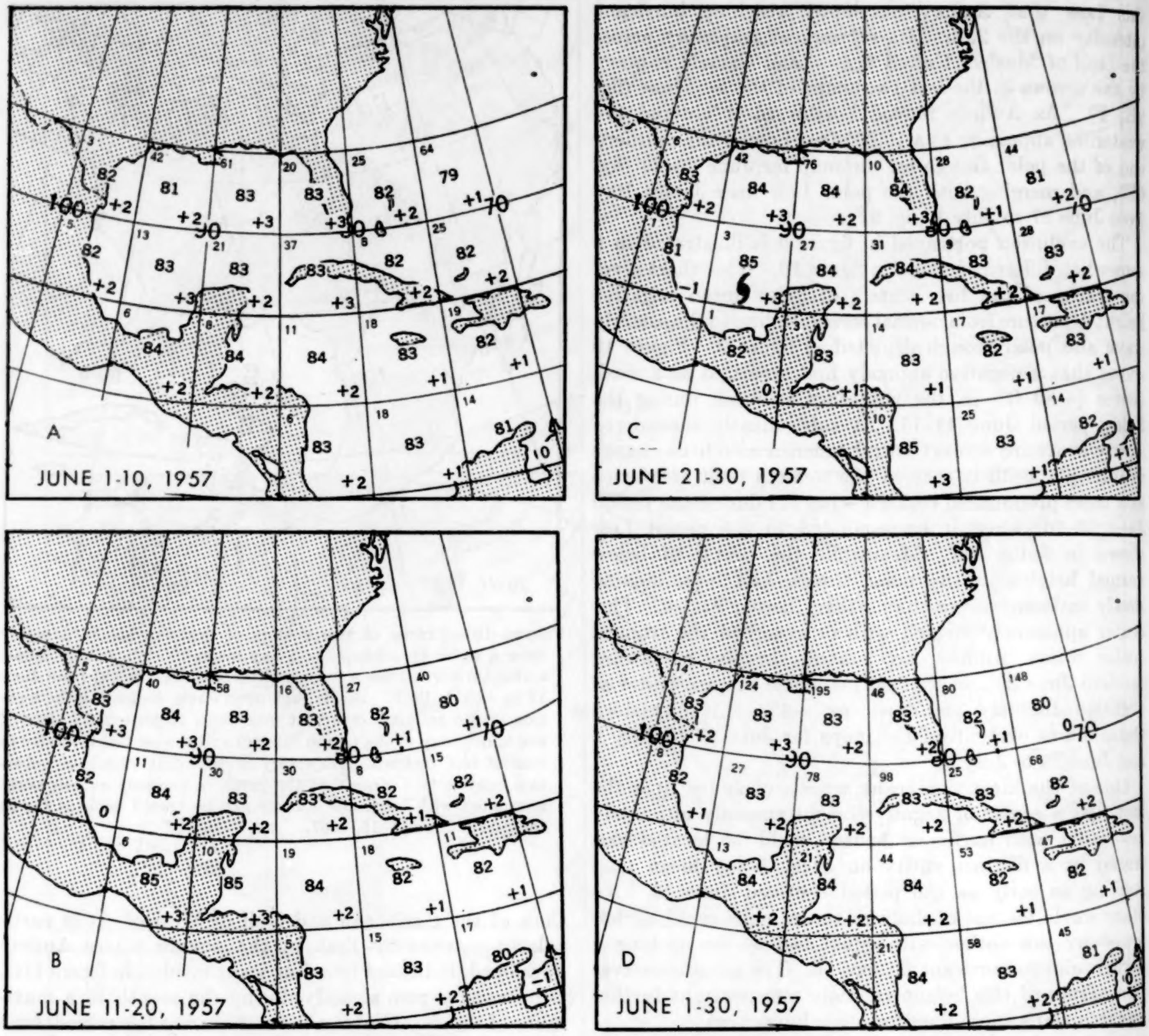

FIGURE 11.—Mean sea surface temperatures (° F.) by 5° squares for each decade in June 1957 (A, B, C) and for the month as a whole (D). Numbers in lower right hand corner of each box give the departure from normal in ° F., figures in upper left give the number of ship observations (from daily synoptic maps) on which the data are based. Water temperatures were especially warm in the area where Audrey formed (indicated by the hurricane symbol in C).

the westerlies during a period with considerable amplitude."

That these conditions generally existed in this case is indicated by figure 12, which gives the 5-day mean contours at the 200-mb. level for June 22–26, the period just prior to and during which Audrey (located by the hurricane symbol) actually developed (on June 25). A similar development early in the month, when the sea surface was already warm (fig. 11 A, B) was precluded by the presence of the southern branch of the jet stream shown in figure 5 (A and B), since the Gulf of Mexico was then in the zone of baroclinic westerlies. It was only later in the month, when the jet was farther north and an upper level anticyclone began to develop in the Tropics, that hurricane formation was favored. Thus the transition within the month of June (described in section 3) from a spring type to a summer type of circulation was an important part of the climatological background for hurricane Audrey.

Audrey's track, subsequent to its formation, can also be related to the mean circulation. Namias [9] showed that the paths of both Atlantic hurricanes and Pacific typhoons were roughly parallel to the isopleths of 700-mb. height departure from normal on monthly mean maps for Septem-

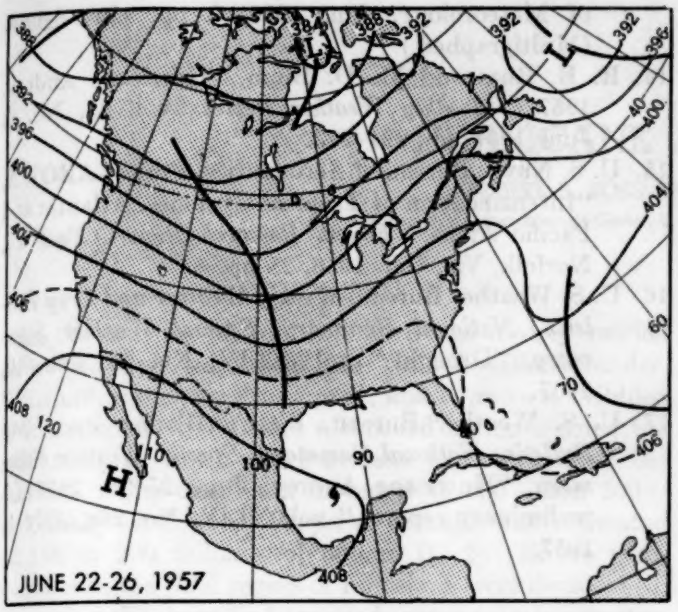

FIGURE 12.—Five-day mean 200-mb. contours (in hundreds of feet) for June 22–26, 1957, the period just prior to and during the development of Audrey. In the area where Audrey formed (indicated by the hurricane symbol) the flow was northerly, and the curvature changed from cyclonic to anticyclonic.

ber 1944 and 1938. A similar relation existed in this case, as can be seen by comparing the trajectory of hurricane Audrey from June 25 to 29 shown in figure 9E with either the 5-day mean 700-mb. anomalies for the same period, given as dotted lines in figure 6D, or the monthly mean anomalies in figure 4.

Also striking was the manner in which this hurricane moved sharply northward along or just east of the axis of the mean trough (fig. 9E). Even after the storm became extratropical in character (about June 28) it crossed the mean contours toward lower height, as illustrated in figure 9F for the period from June 27 to July 1. This tendency for Audrey to move up the trough line may reflect a force driving cyclonic vortices toward regions of higher absolute vorticity, as postulated by Kuo [8] and previously illustrated for extratropical cyclones [6]. Even if this relation is merely a statistical reflection of the effect of the storm upon 700-mb. heights in the region it traverses, it can still be useful as a consistency check and as a prognostic aid in interpreting the mean flow pattern in terms of its daily components. At any rate, this type of behavior can be noted by comparing hurricane tracks with mean trough positions given in many previous articles of this series; for example, it is illustrated for 5-day mean maps in the articles on weather and circulation for the months of September 1951, August 1954, June 1956, and September 1956, and for 30-day means in the articles for August 1950, September and October 1953, September 1954, August 1955, and August 1956.

One of the more intriguing aspects of Audrey's behavior was the way it accelerated and deepened rapidly from a central pressure of 995 mb. in Tennessee on the morning of June 28 to a pressure of 974 mb. just northeast of Lake Huron on the 29th (fig. 9F). This deepening occurred through combination of the hurricane with a wave which formed on the polar front near Chicago on the 28th. A more complete discussion of this process can be found in the following article [14]. It was accompanied by rapid eastward motion of the mean trough from the Mississippi Valley to the Appalachians (fig. 9F), so that during the last 5 days of June the east coast region was occupied by cyclonic instead of anticyclonic flow for the first time in 3 weeks. At the same time a new mean trough extended along the west coast from 20° N. to 60° N., and a mean ridge occupied the Rockies. By the next 5-day period (June 29 to July 3) the 200-mb. jet stream (fig. 5E) was curved sharply anticyclonically in the West and cyclonically in the East. This was indicative of a new circulation regime, more typical of summer, which was to dominate the month of July. These events were reminiscent of the passage of hurricane Hazel in October 1954 [7] since this storm also underwent baroclinic deepening in the northeastern United States coincident with a complete change of circulation pattern over the entire country.

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CORRECTION

MONTHLY WEATHER REVIEW, vol. 85, No. 4, April 1957, p. 120: Legend to figure 1 should read "Relation between dry bulb temperature at 4:45 p. m. PST," instead of "dewpoint temperature."

HURRICANE AUDREY, 1957

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1. INTRODUCTION

On the morning of June 27, hurricane Audrey swirled across the Gulf coast near the Texas-Louisiana border. Communications were disrupted, and as reports dribbled in it was some time before a shocked nation learned the full extent to which the hurricane had devastated the coastline. The death toll mounted to 100—then 200—and finally over 500. Property damage was estimated at 150 to 200 millions of dollars [1, 2]. Entire communities in the tidal region of Louisiana were demolished. Even after the storm had assumed extratropical characteristics, ten lives were lost and property was destroyed in Indiana, Illinois, and New York due to heavy rains and high winds. The storm's influence extended even into Canada, were four persons were killed and winds of 80 m. p. h. were recorded.

During the period June 20 to June 25, an ill-defined easterly wave had moved across the Caribbean Sea to a position at 22.5° N., 93° W., in the Gulf of Mexico, where a tropical depression developed. This easterly wave was difficult to follow as it progressed westward due to the uneven distribution of reports from this area. In correspondence with the Weather Bureau office in New Orleans, La. [2], regarding the formation of hurricane Audrey, the following was received:

> Light westerly winds aloft (mid-levels) were reported from Carmen (Mexico) on June 24th. This was the first definite indication of circulation over the southwest Gulf. That evening the following message was received from Brownsville (Tex.):
>
> CKT 7062 ABRO 250230Z SHRIMP DOCK AT PORT BROWNSVILLE REPORT ONE SHRIMP BOAT IN GULF OF CAMPECHE IN ROUGH WEATHER AT 2230N 9430W WIND STEADY AT 35/40 KTS G55 IN SQUALLS BAROMETER READING THIS MORNING 2990 THIS EVENING 2978 STRONG SEA SENT 0233 HRR

An investigation by Klein [3] on the formation of this tropical depression which developed into Audrey is reported in this issue. He discusses the importance of the broad-scale flow patterns and the sea surface temperature.

2. TROPICAL PHASE

At 0430 GMT on June 25, the first bulletin from the New Orleans Weather Bureau Office [4] was released on the tropical depression which had formed over the Bay of Campeche in the southwestern Gulf of Mexico. Highest winds were estimated to be about 35 to 40 m. p. h. The depression remained nearly stationary for several hours and showed signs of rapid intensification. On the basis of a Navy reconnaissance flight and an earlier excellent report from the SS *Terrier*, the first hurricane advisory was issued by the Weather Bureau at 1800 GMT June 25, stating the tropical depression had reached hurricane strength and was centered near 22.5° N., 93.0° W., or about 380 miles southeast of Brownsville, Tex. The storm was forecast to move northward at 5 m. p. h. and to increase slowly in size and intensity. As the storm moved northward, the winds near the center increased in speed from 75 to over 100 m. p. h., and by 1200 GMT on the 26th it had moved to a position 250 miles east-southeast of Brownsville. At this time the storm was moving northward at about 10 m. p. h. This rate gradually increased until it reached 15 m. p. h. early on the 27th. By 1300 GMT on the 27th the storm was centered just off the Texas-Louisiana coast south of Port Arthur, Tex. Up to this time the highest winds reported on the coast were 75 m. p. h. and the highest tide reported was 7 ft. m. s. l. These were the last reports received from Sabine, Tex., before their communications failed.

At 1530 GMT on the 27th a report from Orange, Tex., stated that after having experienced winds of over 100 m. p. h., the town was now in the dead calm associated with the eye of the storm and awaiting the return of strong winds. The maximum winds at Lake Charles, La., as the storm passed just to the west were 105 m. p. h. Having entered the mainland, the storm rapidly increased its forward momentum and recurved toward the northeast.

The major portion of the damage in the Gulf coast region resulted from high water. Normal diurnal range of the tides for this region is from 1 to 2 ft. Increased heights of the water as a result of Audrey were apparent as early as noon on the 26th at Galveston, Tex., and reached a peak there of 6.2 ft. m. s. l. at 1030 GMT on the 27th. The area affected by tides of 6 ft. m. s. l. or over extended from Galveston to a point 330 miles eastward.

At Cameron Coast Guard Station, La., the water began to rise prominently by 1000 GMT on the 27th and rose at the rate of 1.5 ft. per hour for several hours, reaching a peak in Cameron of 10.6 ft. m. s. l. between 1600 and 1700 GMT on the 27th. This peak was reached after the initial impact of the high winds of the hurricane and before the rise of the secondary winds associated with

FIGURE 1.—Track of hurricane Audrey, 1957. Positions shown are at 6-hour intervals.

the passage of the eye of the storm on shore some 23 miles to the west of Cameron. Waves of between 4 and 5 ft. with a few peaks possibly reaching 8 to 10 ft. were superimposed on this high water. The water remained high until around 2000 GMT, at which time the winds shifted to an offshore direction and the water began to recede.

The highest tides occurred about 40 miles to the east of the region where the center of the hurricane crossed the coast. They were highest on the coast and decreased somewhat inland. At Lake Charles, La., a tide of 7 ft. m. s. l. was recorded. The tidal region along the Gulf coast affected by the high water is quite extensive, being near sea level, and in some instances below sea level, for considerable distances inland. For the period of high water, these tidal regions were inundated as far as 10 to 20 miles inland.

Some of the reported low barometric readings and the times of their occurrence on June 27 are as follows:

	(mb.)	(GMT)
Galveston, Tex.	986	1200
Cameron, La.	959	1430
Port Arthur, Tex.	966	1523
Beaumont, Tex.	971	1528
Lake Charles, La.	972	1740

On the morning of the 28th the storm, which was centered over west central Tennessee, had lost its hurricane strength winds and had entered its extratropical phase. As the storm was moving from the coast to this position, several tornadoes developed in Mississippi, Louisiana, and Alabama. In Mississippi and Louisiana, one life was lost and several buildings were damaged. In Alabama 14 people were injured and property damage was estimated at $600,000 as a result of these tornadoes [1]. For Audrey's track and associated surface features, see figures 1 and 2.

Between 0000 GMT and 1200 GMT on the 25th, a polar trough at the 200-mb. level moved eastward through the Mississippi Valley. An extension of this trough produced a shear line through south-central Texas (fig. 3). The northern portion of the polar trough continued its eastward movement, while the shear line through Texas was accentuated and slowly retrogressed. By 1200 GMT on the 25th, the 200-mb. winds at Brownsville and Corpus Christi, Tex., which had been north-northwesterly, had backed sharply and were blowing from 210°. These winds continued to back slowly as Audrey moved northward. At this time a weak anticyclonic circulation in the eastern Gulf region, which had become more pronounced, facilitated the outflow above the storm and favored the further development of the hurricane [5].

3. EXTRATROPICAL PHASE

The extratropical phase of the storm presented some noteworthy dynamic aspects in conjunction with the

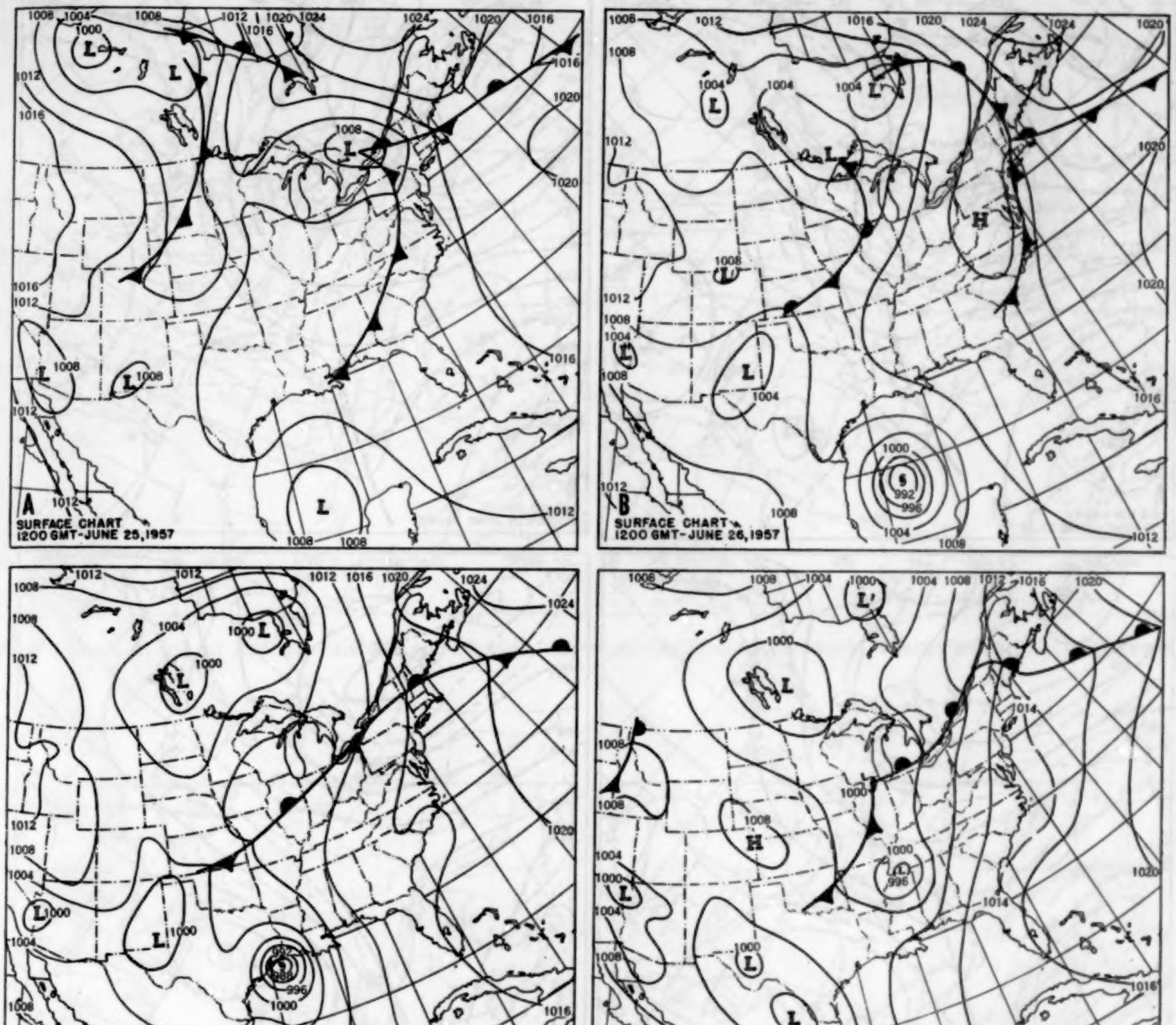

FIGURE 2.—Surface weather charts for 1200 GMT June 25–30, 1957.

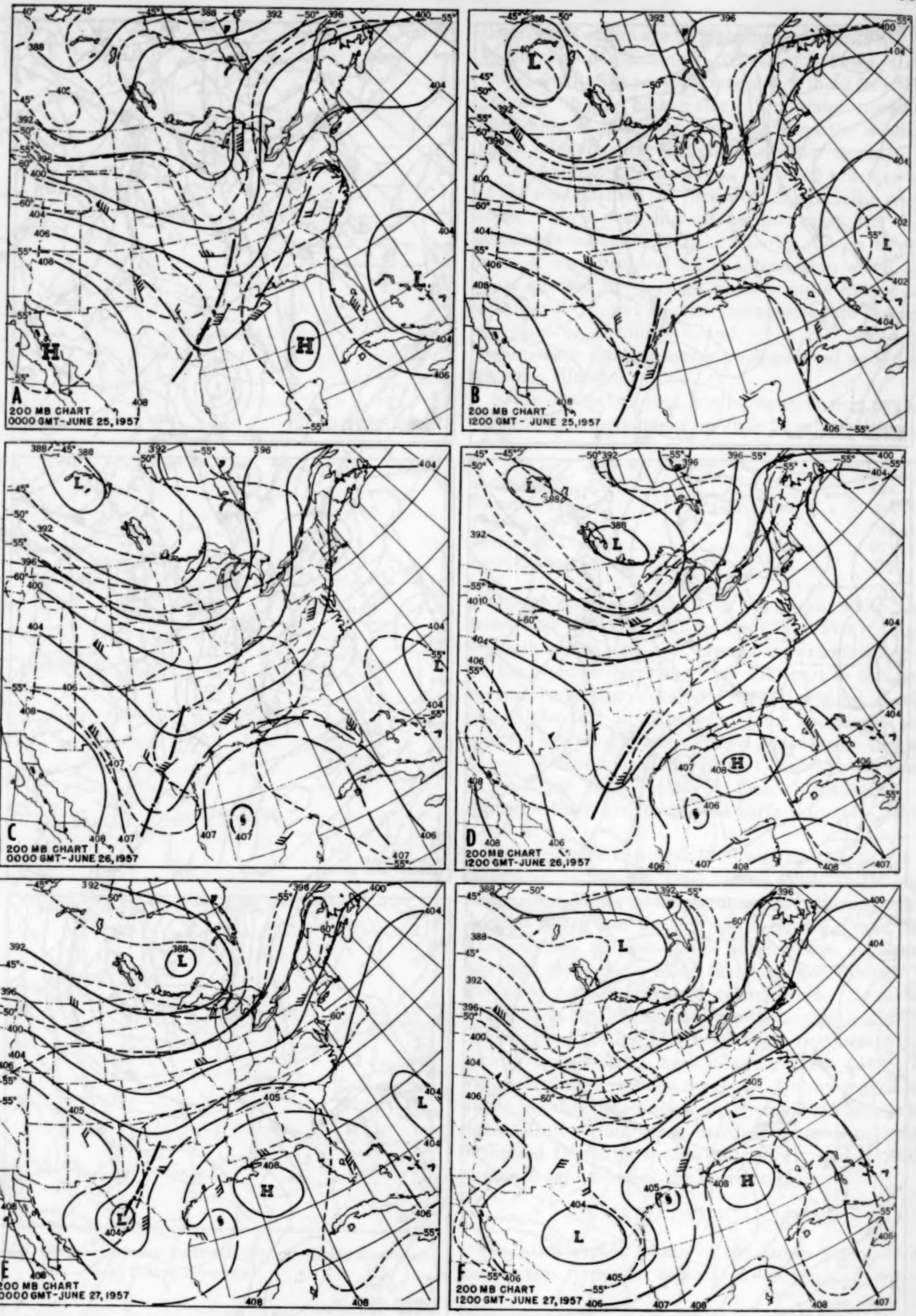

FIGURE 3.—200-mb. charts shown at 12-hour intervals from 0000 GMT June 25 to 1200 GMT June 27, 1957. Contours (solid lines) are in hundreds of geopotential feet; isotherms (dashed lines), in ° C.

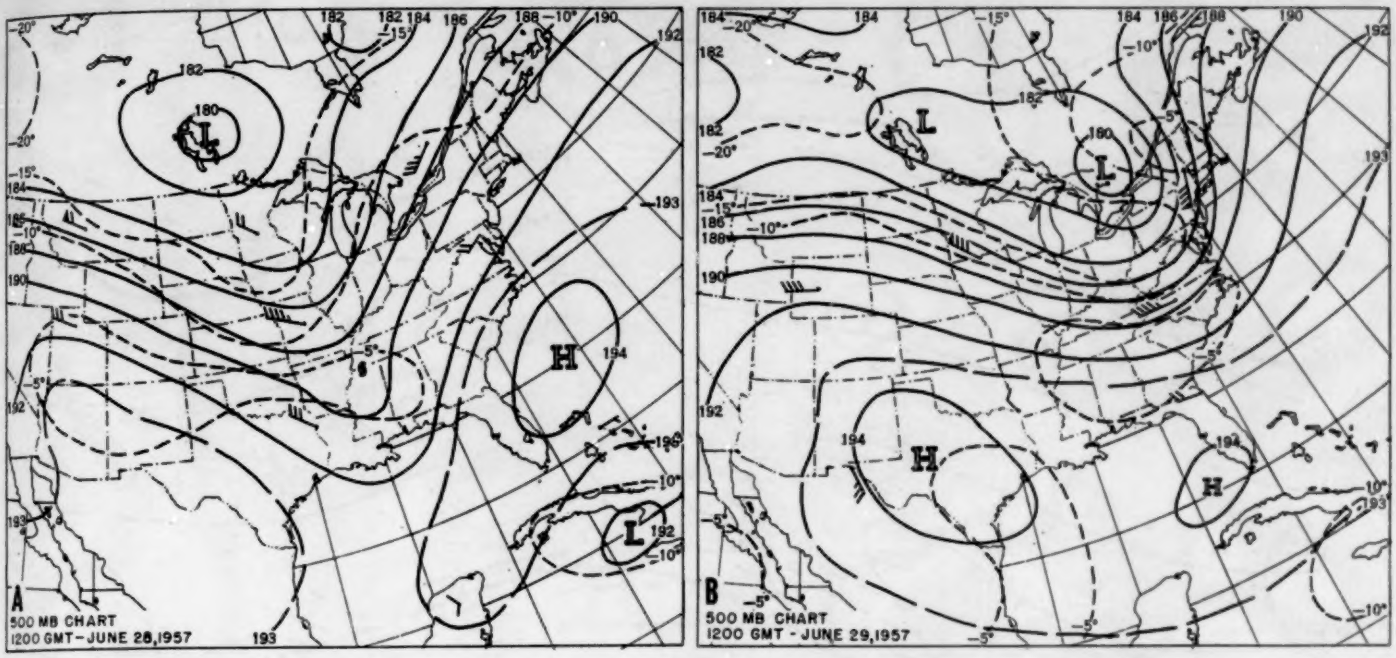

FIGURE 4.—500-mb. charts for 1200 GMT, June 28 and 29, 1957. Contours (solid) are in hundreds of geopotential feet; isotherms (dashed), in ° C.

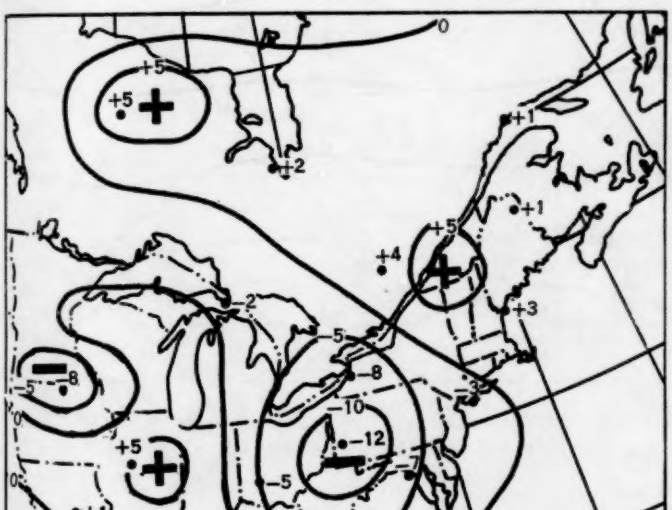

FIGURE 5.—500-mb. 12-hour temperature change chart for the period 0000 GMT to 1200 GMT June 29, 1957. Isolines of temperature change are at 5° C. intervals.

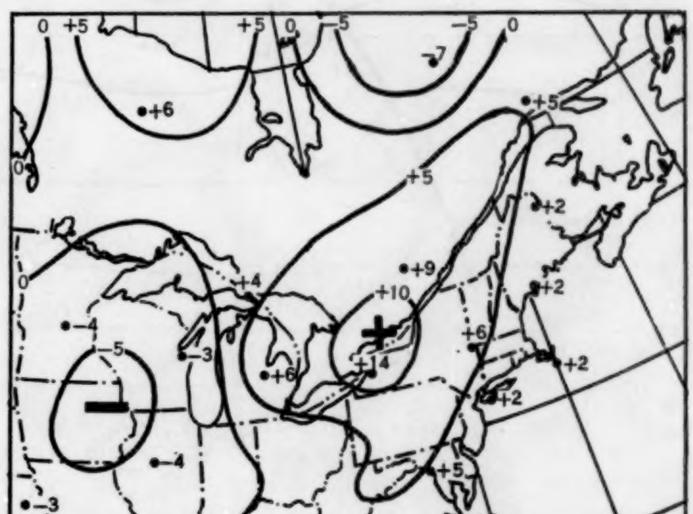

FIGURE 6.—200-mb. 12-hour temperature change chart for 0000 to 1200 GMT June 29, 1957. Isolines of temperature change are at 5° C. intervals.

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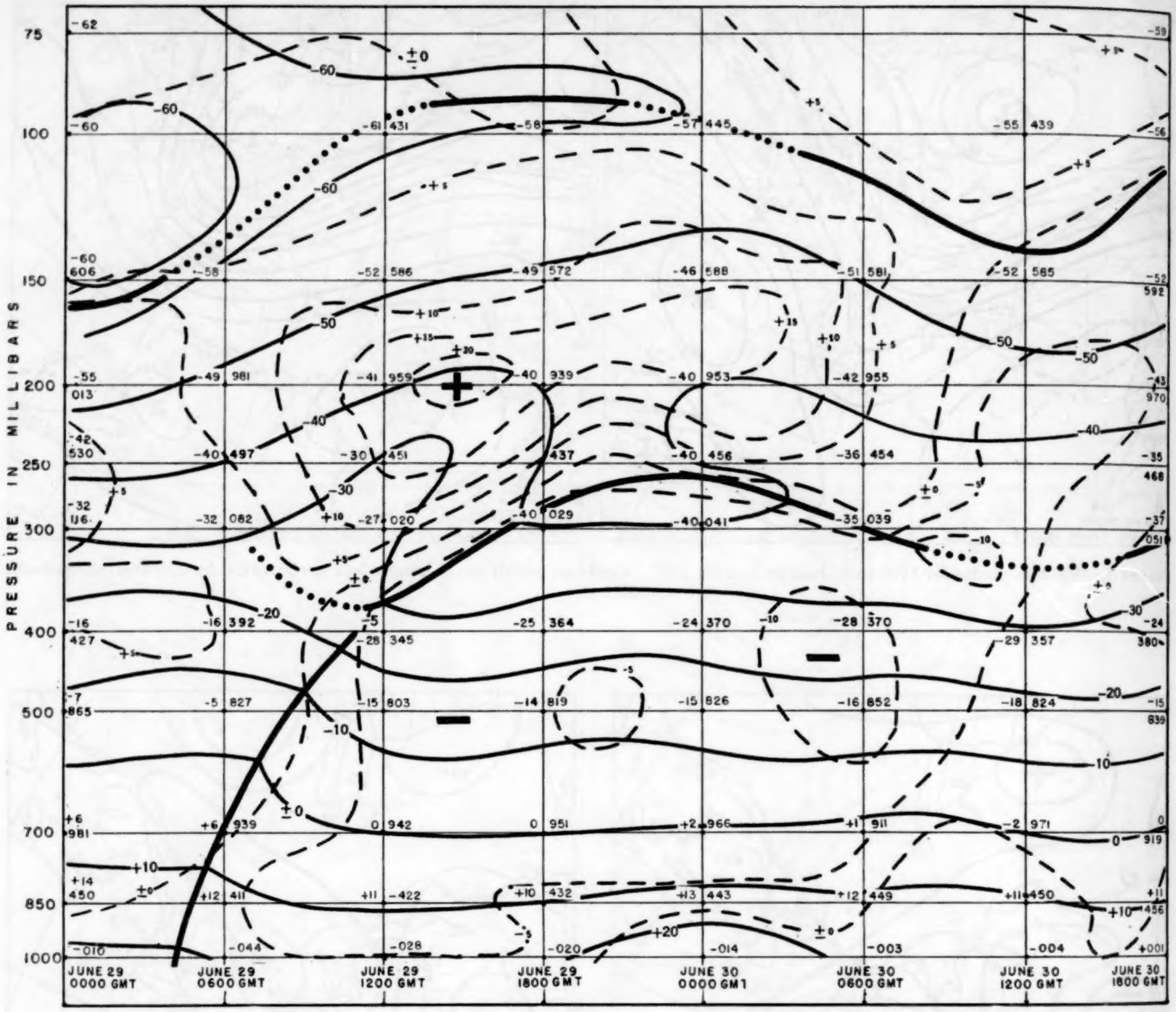

FIGURE 7.—Time cross section for Buffalo, N. Y., from 0000 GMT June 29 to 1800 GMT June 30, 1957. Isotherms in ° C. are light solid lines. 24-hour temperature changes at 5° C. intervals are dashed lines. Fronts and tropopauses are heavy solid lines, heavy dotted where indistinct.

amalgamation of Audrey with a polar wave. This union resulted in a storm of major proportions which affected much of the Mississippi-Ohio Valley region, eastern United States, and eastern Canada. In the Mississippi-Ohio Valley region most of the storm damage resulted from heavy rains, while high winds accounted for nearly all the damage in the eastern United States and Canada. The heavy, flood-producing rains which occurred in the Mississippi-Ohio Valley on June 27, 28, and 29 cannot be attributed completely to Audrey. These rains were frontal in nature. However, there is little doubt that Audrey augmented the available precipitable moisture contributing to the heavy rains [1].

On the 28th, when Audrey was in the process of assuming extratropical characteristics, a wave formed on a polar front in the vicinity of Chicago, Ill. At 1200 GMT on the 28th, the central pressure was 995 mb. for Audrey and 1,000 mb. for the wave on the polar front (fig. 2D). Just 24 hours later the union of these storms was complete, with the storm centered about 140 miles north of Buffalo, N. Y., in southwestern Quebec, Canada. At this time, the storm had reached maximum intensity as an extratropical storm with a central pressure of 974 mb. This approached the lowest pressure associated with Audrey in its tropical phase. It was this rapid intensification of the storm which resulted in the high winds observed in the eastern United States and Canada. Winds of 95 to 100 m. p. h. were reported at Jamestown, N. Y. [1].

In the deepening of the polar wave, it was difficult to differentiate between the contribution made by the

remnants of Audrey and that made by cyclogenesis in the westerly flow aloft. As Audrey moved inland she became aligned with, and eventually absorbed into, an intensifying polar trough progressing eastward. At the 500-mb. level, the warm air moved rapidly northeastward, which resulted in an intensifying thermal gradient over the northeastern United States (fig. 4). In the 24-hour period between 1200 GMT on the 28th and 1200 GMT on the 29th, maximum cooling in the troposphere was centered near Pittsburgh, Pa. (fig. 5), where at the 500-mb. level 9° C. of cooling occurred; 8° of this cooling was in the last 12 hours. In the stratosphere during the same interval, maximum warming at the 200-mb. level was centered near Buffalo, N. Y. (fig. 6), where 16° C. of warming occurred, 14° of which took place in the last 12 hours of the period. The time cross section for Buffalo (fig. 7) graphically shows the temperature change which occurred in the troposphere and stratosphere.

Maximum intensification of the surface storm ensued when the upper-air low pressure center became nearly vertical with the surface feature. In conjunction with this intensification, a low tropopause formed as shown on the time cross section (fig. 7). The baroclinic nature of this development, which contributed to the rapid intensification of the storm, can be seen by an inspection of the isotherm field on the 500-mb. chart shown in figure 5. The 24-hour change shown in the temperature field with the intensification of the thermal gradient in northeastern United States is quite spectacular.

It appears that even without the influence of Audrey the baroclinic structure in the westerlies would have been sufficient to develop a storm of major proportions. Stratospheric warming is considered to have been of prime importance in the extratropical cyclogenesis. Vederman [6] has discussed the importance of stratospheric influences to cyclogenesis at the surface. Haurwitz [7] relates the stratosphere to the troposphere in the development of cyclones. The time cross section for Buffalo (fig. 7), with the 24-hour temperature changes, shows the spectacular magnitude of the stratospheric warming just above the formation of the low tropopause in relation to the cooling which took place in the troposphere.

Audrey's contribution cannot be ignored—certainly with the absorption of the tropical Low into the polar trough cyclonic vorticity was added and the thermal distribution was affected, contributing to the baroclinicity of the development. The limited time allotted to the preparation of this article, however, precludes any attempt to assign quantitative values to the tropical influences adding to the development of the extratropical storm.

ACKNOWLEDGMENTS

The authors wish to express their thanks to the staff of the National Weather Analysis Center for their aid in the preparation of this report. We are also indebted to Messrs. Robert H. Simpson, Gordon E. Dunn, Stephen Lichtblau, and their staffs for information supplied and for their review of this article; also to Mr. D. Lee Harris for his assistance in the preparation of the section on tides.

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2. Stephen Lichtblau, Personal correspondence.
3. William H. Klein, "The Weather and Circulation of June 1957—Including an Analysis of Hurricane Audrey in Relation to the Mean Circulation," *Monthly Weather Review*, vol. 85, No. 6, June 1957, pp. 208–220.
4. U. S. Weather Bureau, *Hurricane Audrey, June 24–27, 1957*, Preliminary Report, Washington, D. C., July 8, 1957.
5. U. S. Navy, Bureau of Aeronautics, Project AROWA, "Intensification of Tropical Cyclones Atlantic and Pacific Areas," *Fourth Research Report, Task 12*, Oct. 1956, 28 pp.
6. Joseph Vederman, "Changes in Vertical Mass Distribution over Rapidly Deepening Lows," *Bulletin of the American Meteorological Society*, vol. 30, No. 9, Nov. 1949, pp. 303–309.
7. Bernhard Haurwitz, *Dynamic Meteorology*, McGraw-Hill Book Co., Inc., New York and London, 1941. (See pp. 320–334.)

Change in Climatological Charts

Beginning on June 1, 1957, a change was made in surface observation times. This has had the following effect on the charts listed below. Charts not listed are not affected.

Chart V–B. Snow depth is now measured at 7 a. m. EST instead of 7:30.

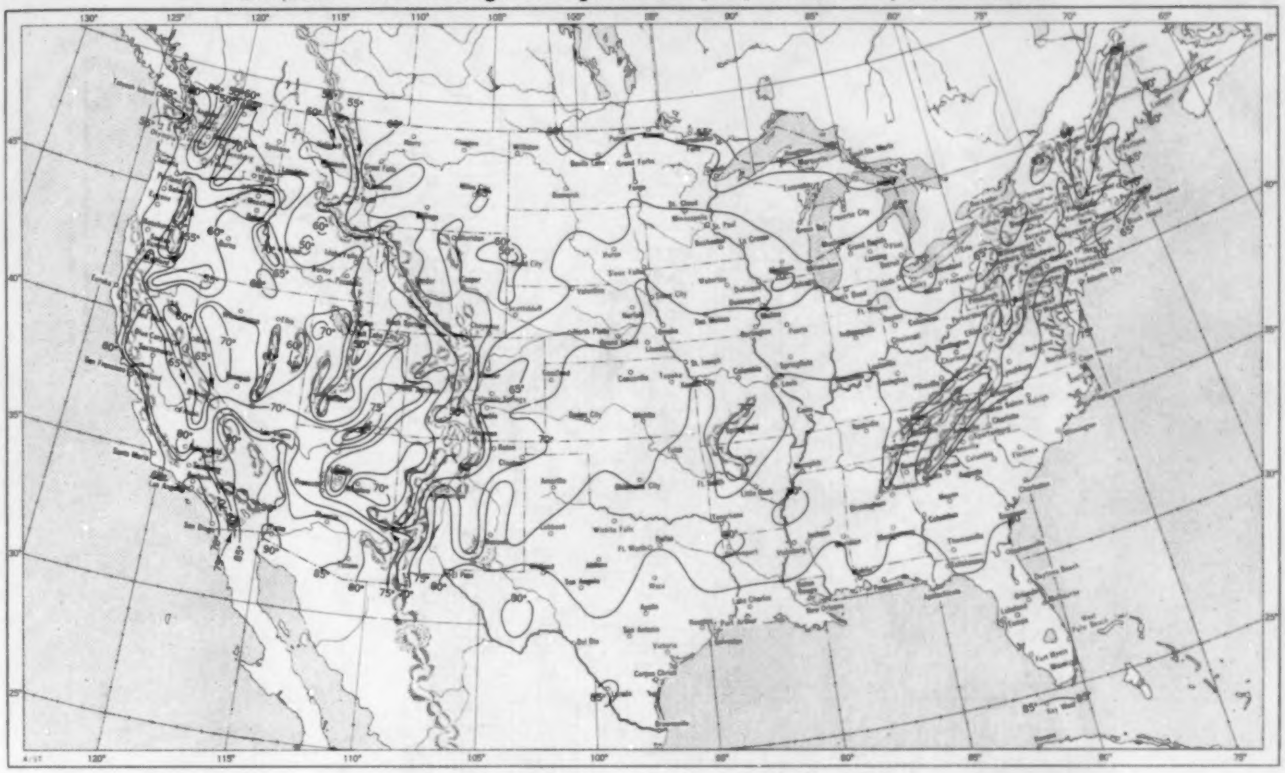
Charts IX and X. Circle indicates cyclone and anticyclone positions at 7 a. m. EST instead of 7:30.

Chart XI. Average sea-level pressure is computed from the 7 a. m. and p. m. EST readings instead of 7:30 a. m. and p. m.

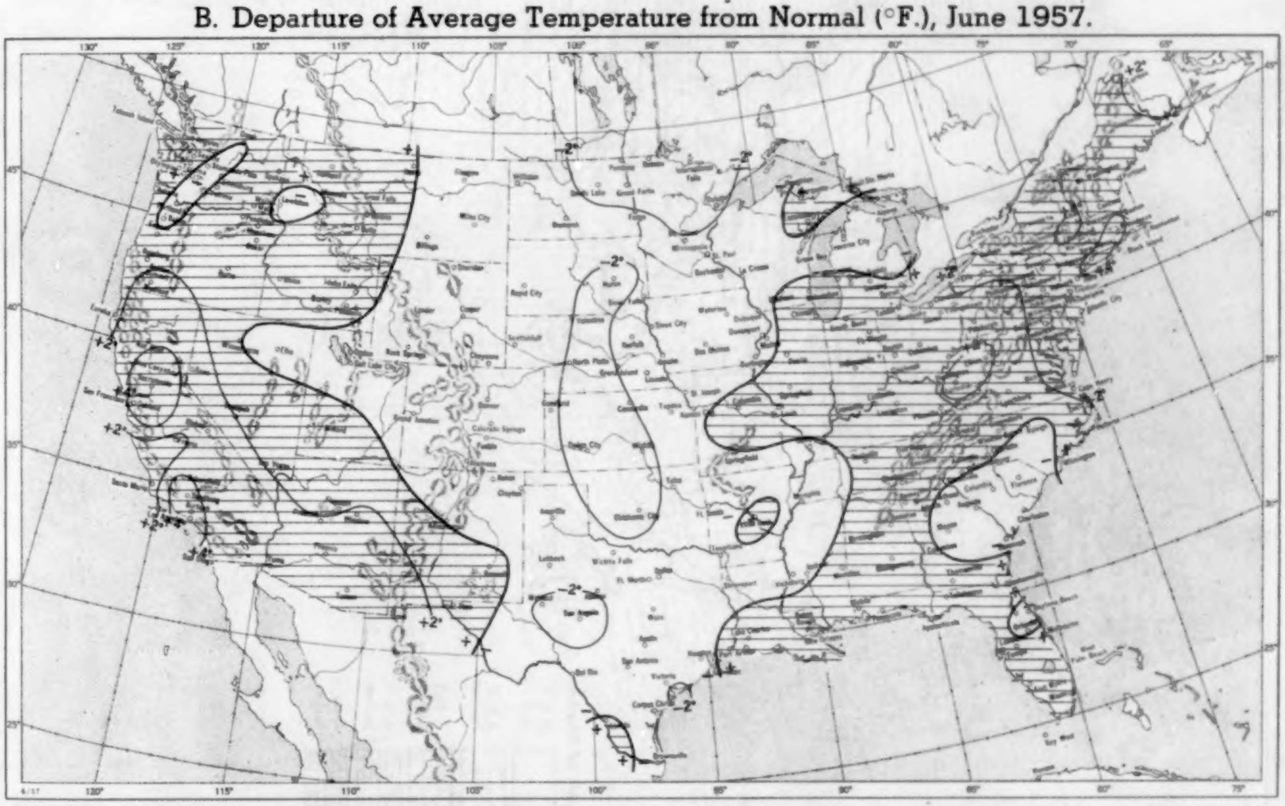
Charts XII–XVII. All the upper-air charts are now for 1200 GMT instead of 0300 GMT. All winds are based on rawinsonde observations. Use of pibal data has been discontinued in these charts.

U. S. GOVERNMENT PRINTING OFFICE: 1957

Chart I. A. Average Temperature (°F.) at Surface, June 1957.



B. Departure of Average Temperature from Normal (°F.), June 1957.

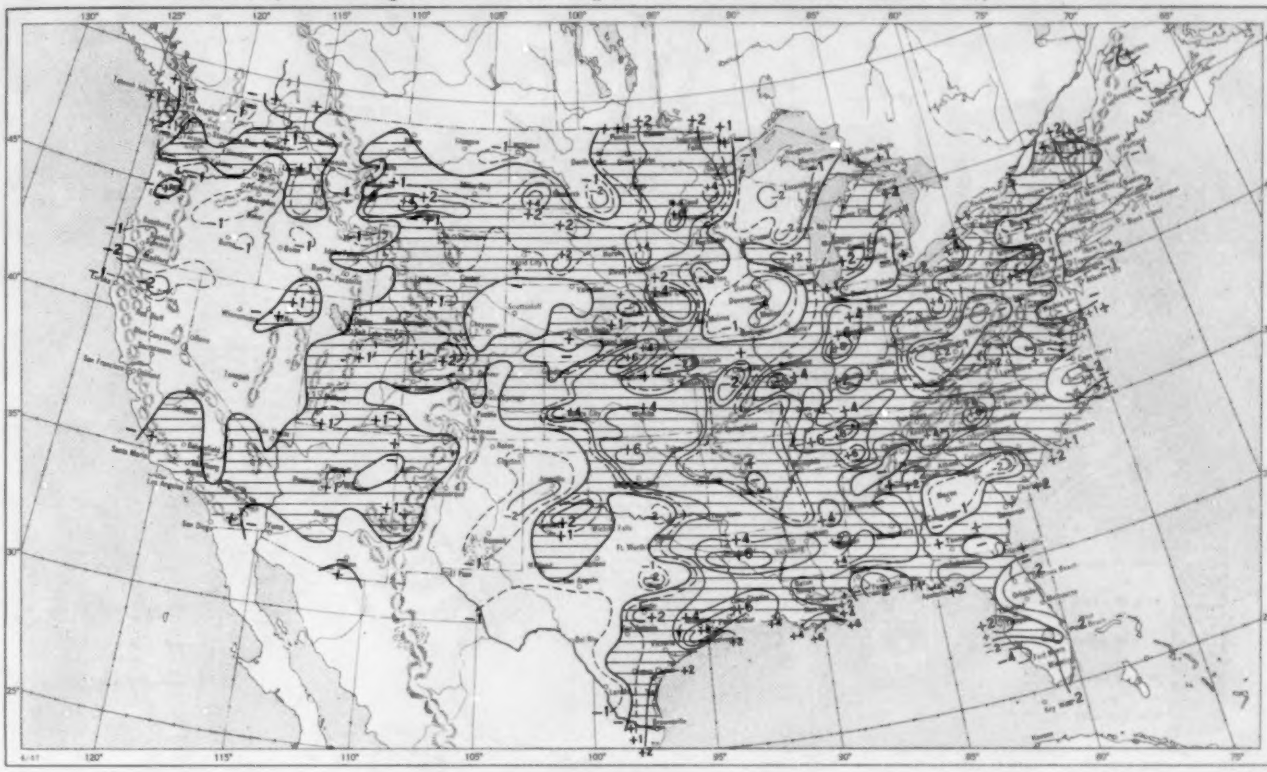


A. Based on reports from over 900 Weather Bureau and cooperative stations. The monthly average is half the sum of the monthly average maximum and monthly average minimum, which are the average of the daily maxima and daily minima, respectively.
B. Departures from normal are based on the 30-yr. normals (1921-50) for Weather Bureau stations and on means of 25 years or more (mostly 1931-55) for cooperative stations.

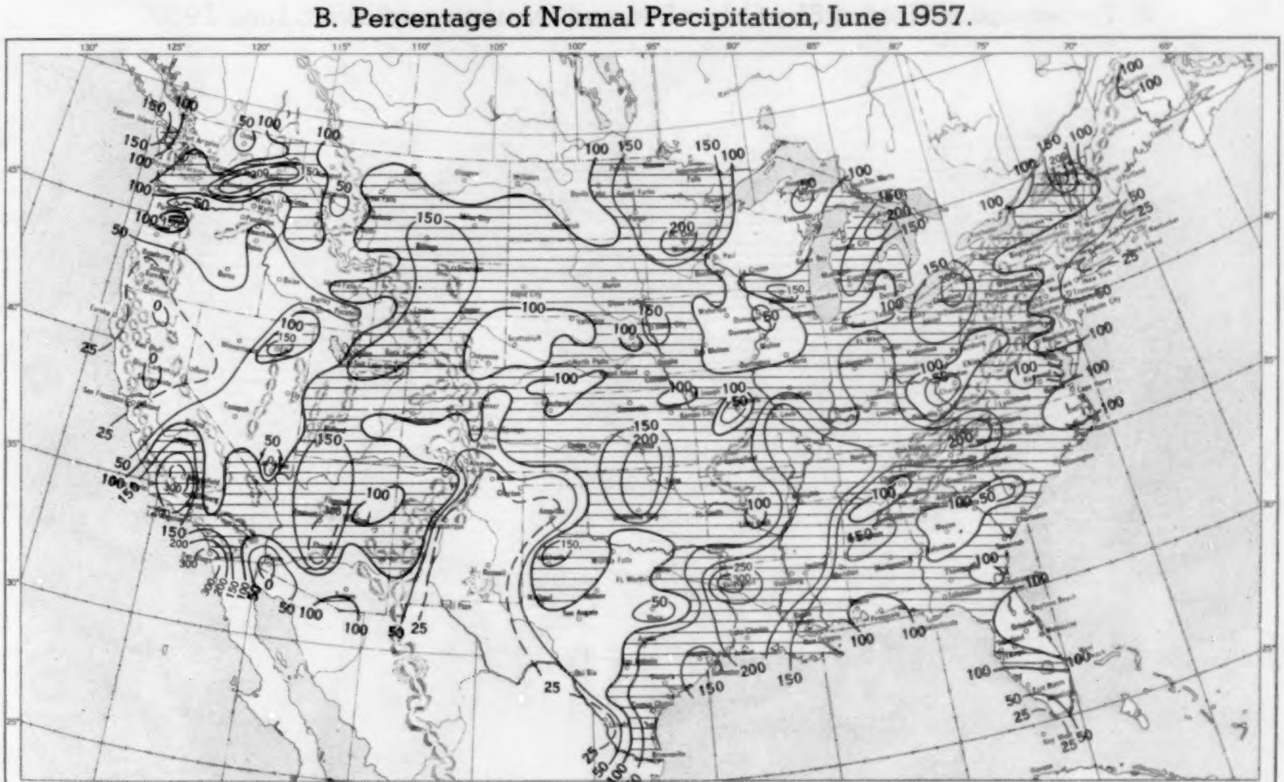
Chart II. Total Precipitation (Inches), June 1957.

Based on daily precipitation records at about 800 Weather Bureau and cooperative stations.

Chart III. A. Departure of Precipitation from Normal (Inches), June 1957.

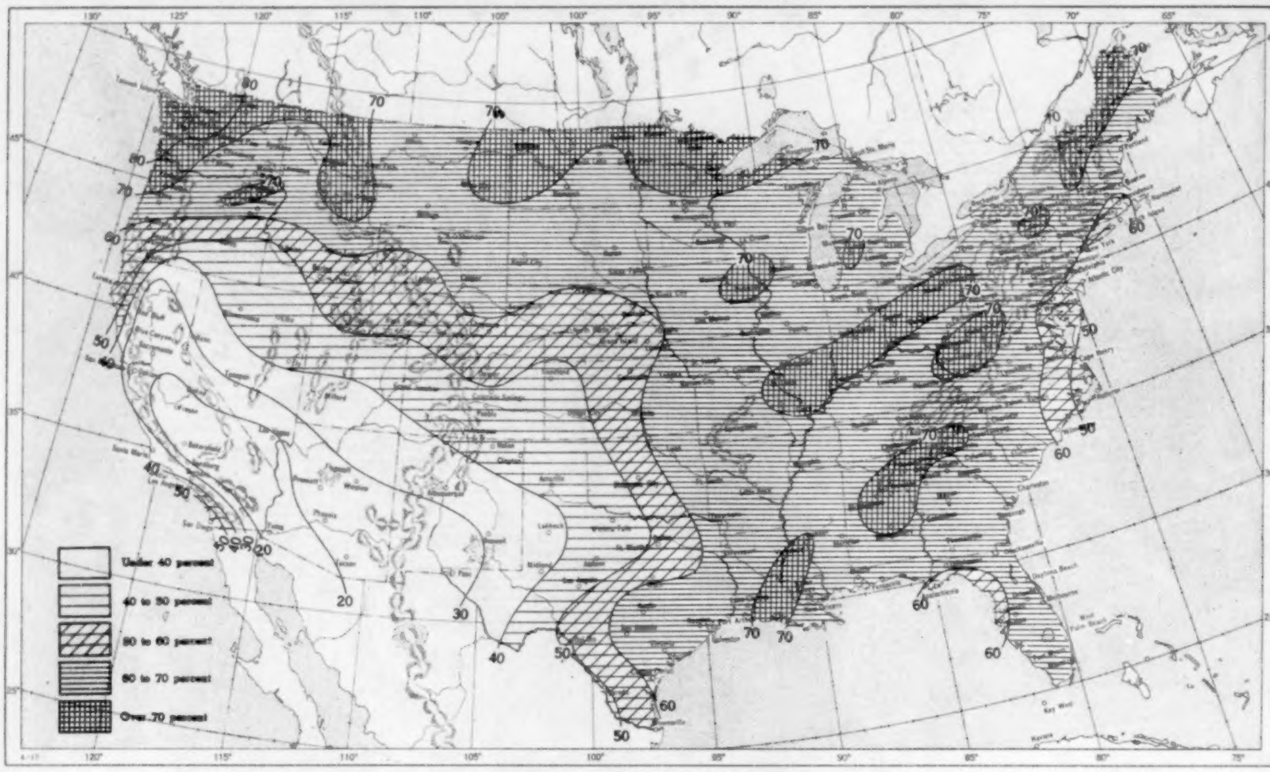


B. Percentage of Normal Precipitation, June 1957.

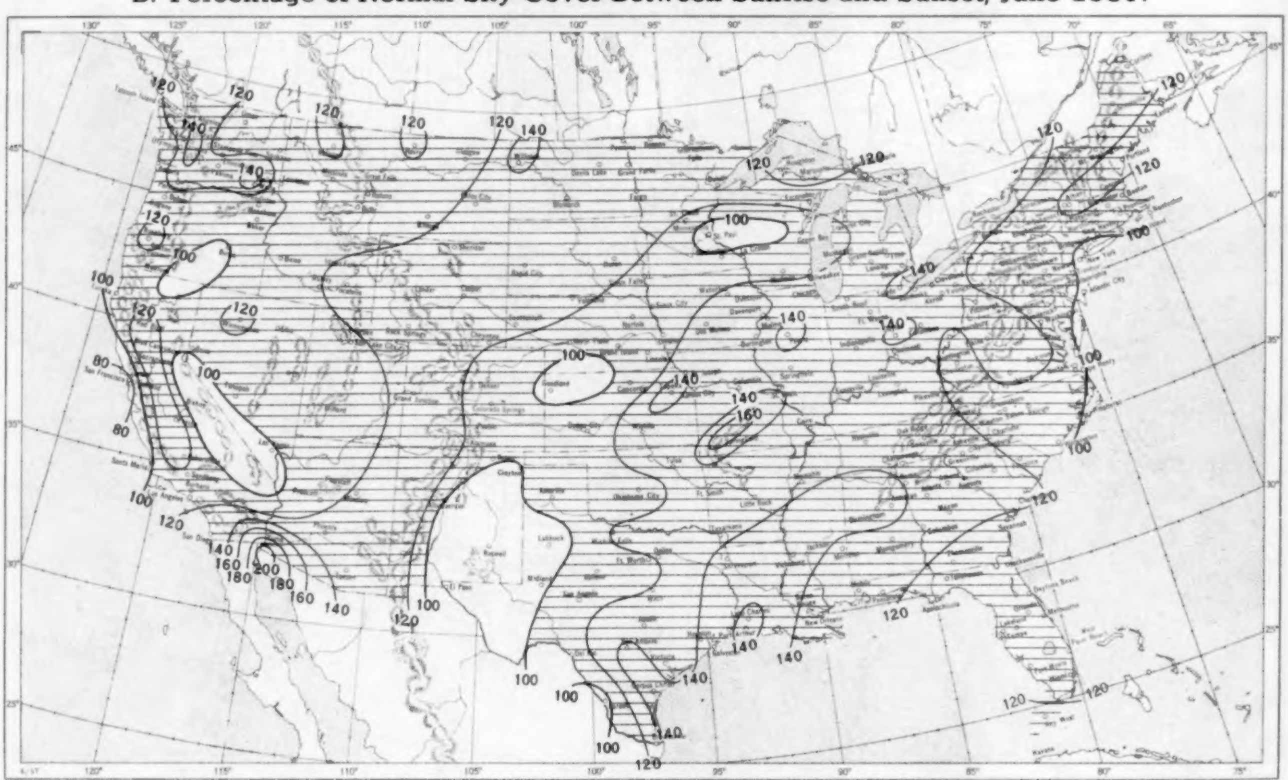


Normal monthly precipitation amounts are computed from the records for 1921-50 for Weather Bureau stations and from records of 25 years or more (mostly 1931-55) for cooperative stations.

Chart VI. A. Percentage of Sky Cover Between Sunrise and Sunset, June 1957.

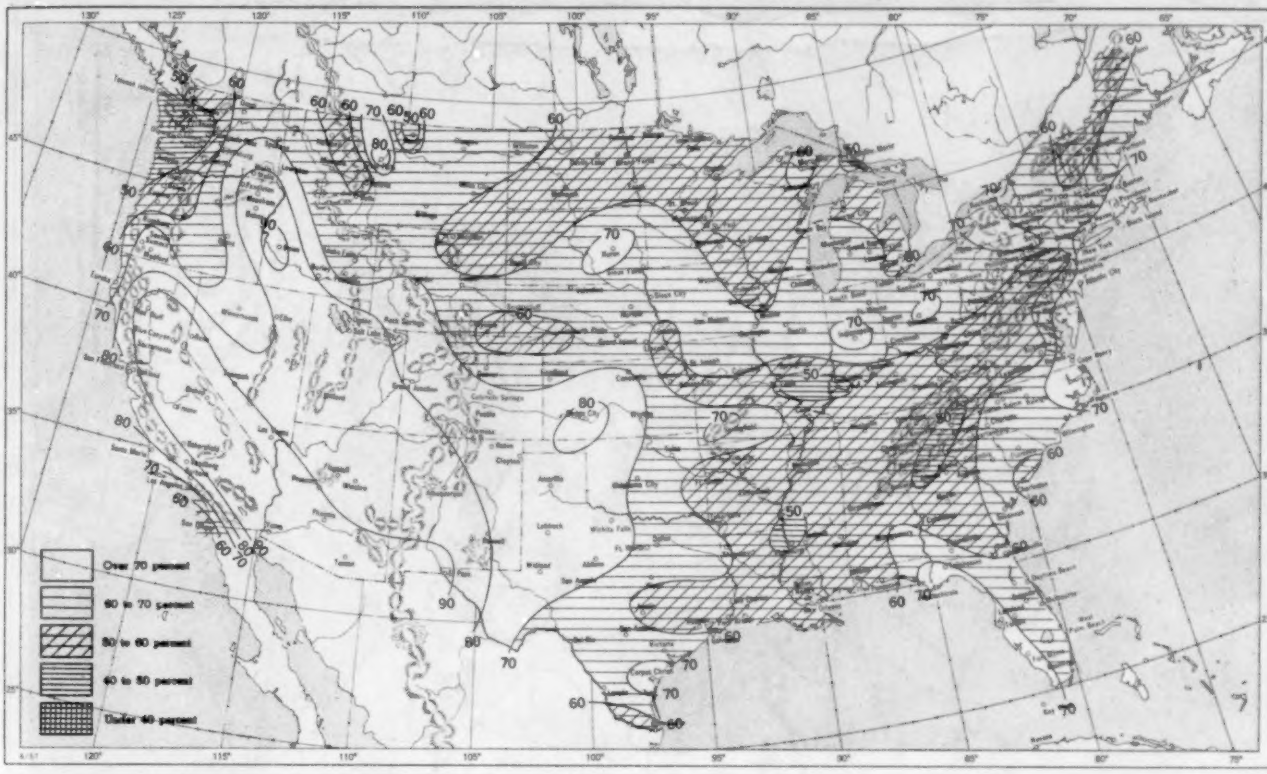


B. Percentage of Normal Sky Cover Between Sunrise and Sunset, June 1957.



A. In addition to cloudiness, sky cover includes obscuration of the sky by fog, smoke, snow, etc. Chart based on visual observations made hourly at Weather Bureau stations and averaged over the month. B. Computations of normal amount of sky cover are made for stations having at least 10 years of record.

Chart VII. A. Percentage of Possible Sunshine, June 1957.



B. Percentage of Normal Sunshine, June 1957.

A. Computed from total number of hours of observed sunshine in relation to total number of possible hours of sunshine during month. B. Normals are computed for stations having at least 10 years of record.

Chart VIII. Average Daily Values of Solar Radiation, Direct + Diffuse, June 1957. Inset: Percentage of Mean Daily Solar Radiation, June 1957. (Mean based on period 1951-55.)

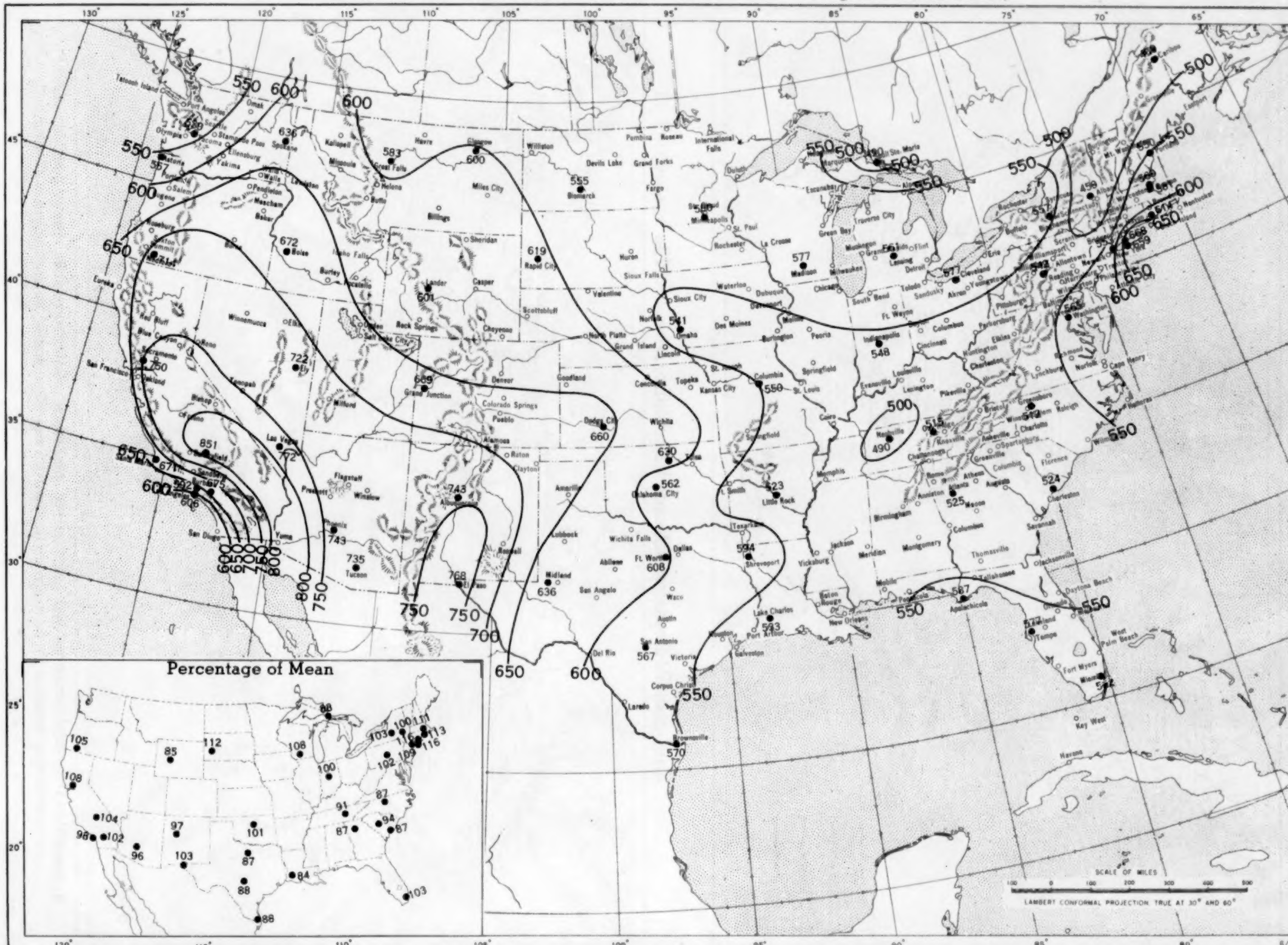
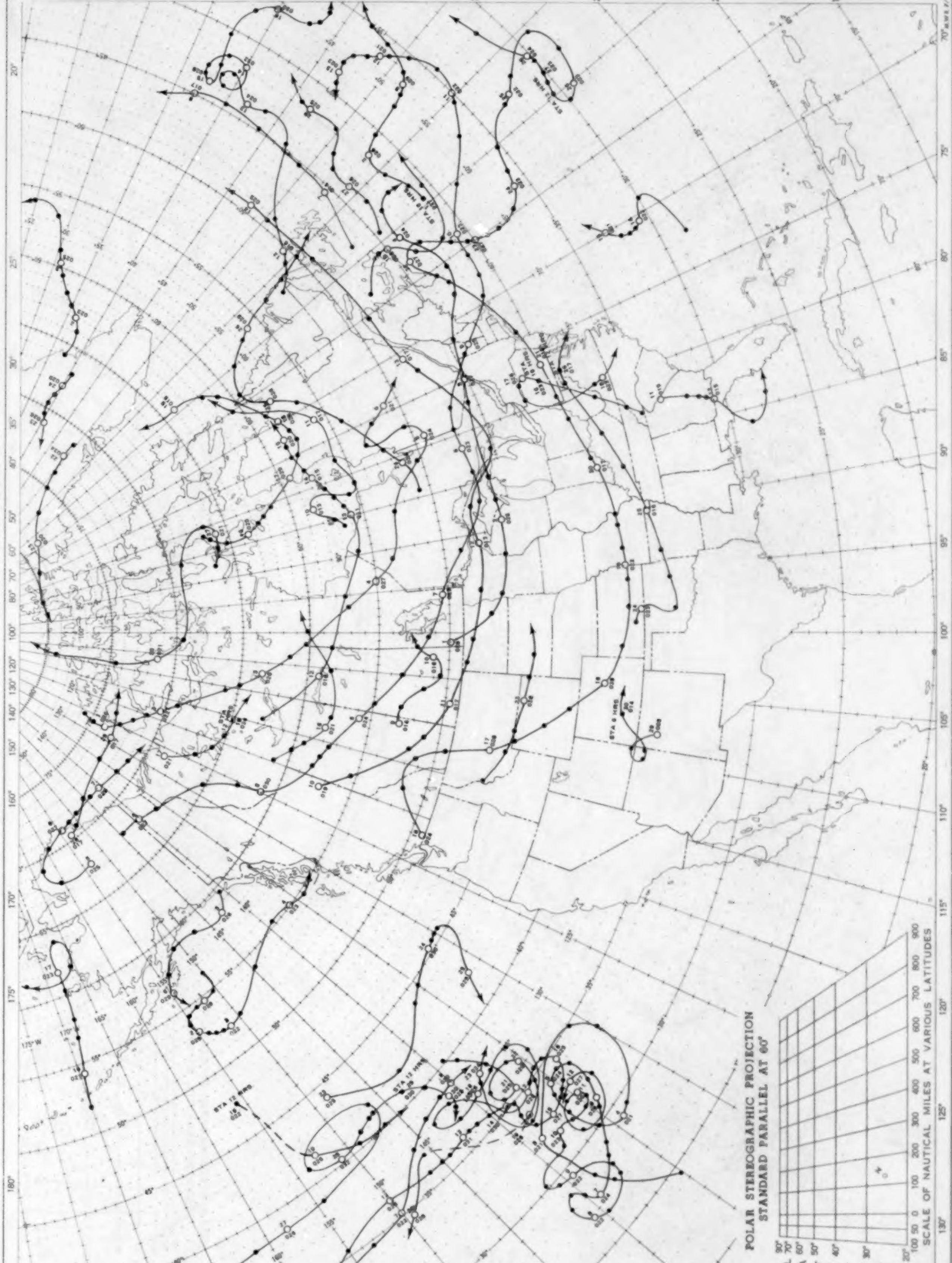


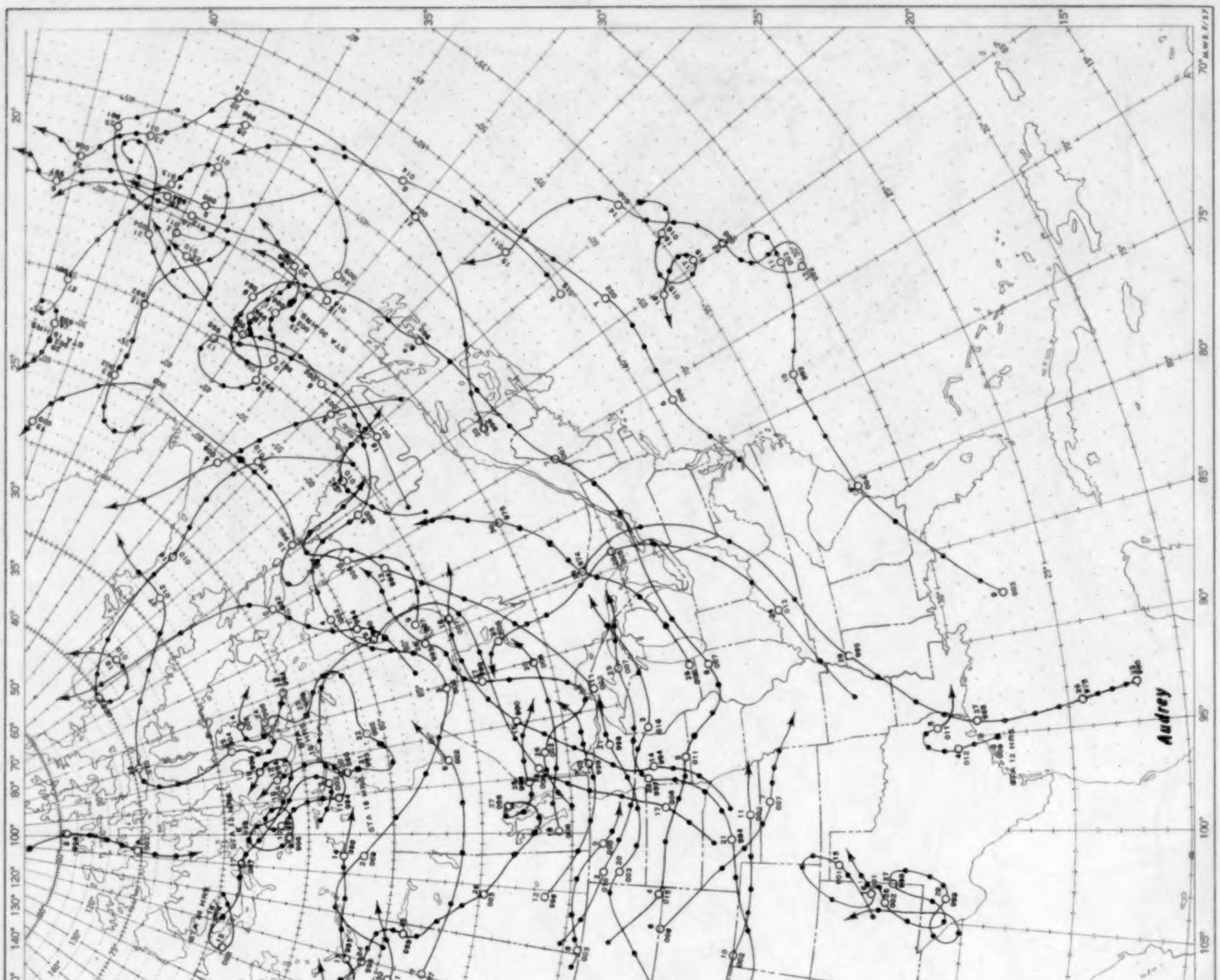
Chart shows mean daily solar radiation, direct + diffuse, received on a horizontal surface in langleys (1 langley = 1 gm. cal. cm. $^{-2}$). Basic data for isolines are shown on chart. Further estimates are obtained from supplementary data for which limits of accuracy are wider than for those data shown. The inset shows the percentage of the mean based on the period 1951-55.

Chart IX. Tracks of Centers of Anticyclones at Sea Level, June 1957.



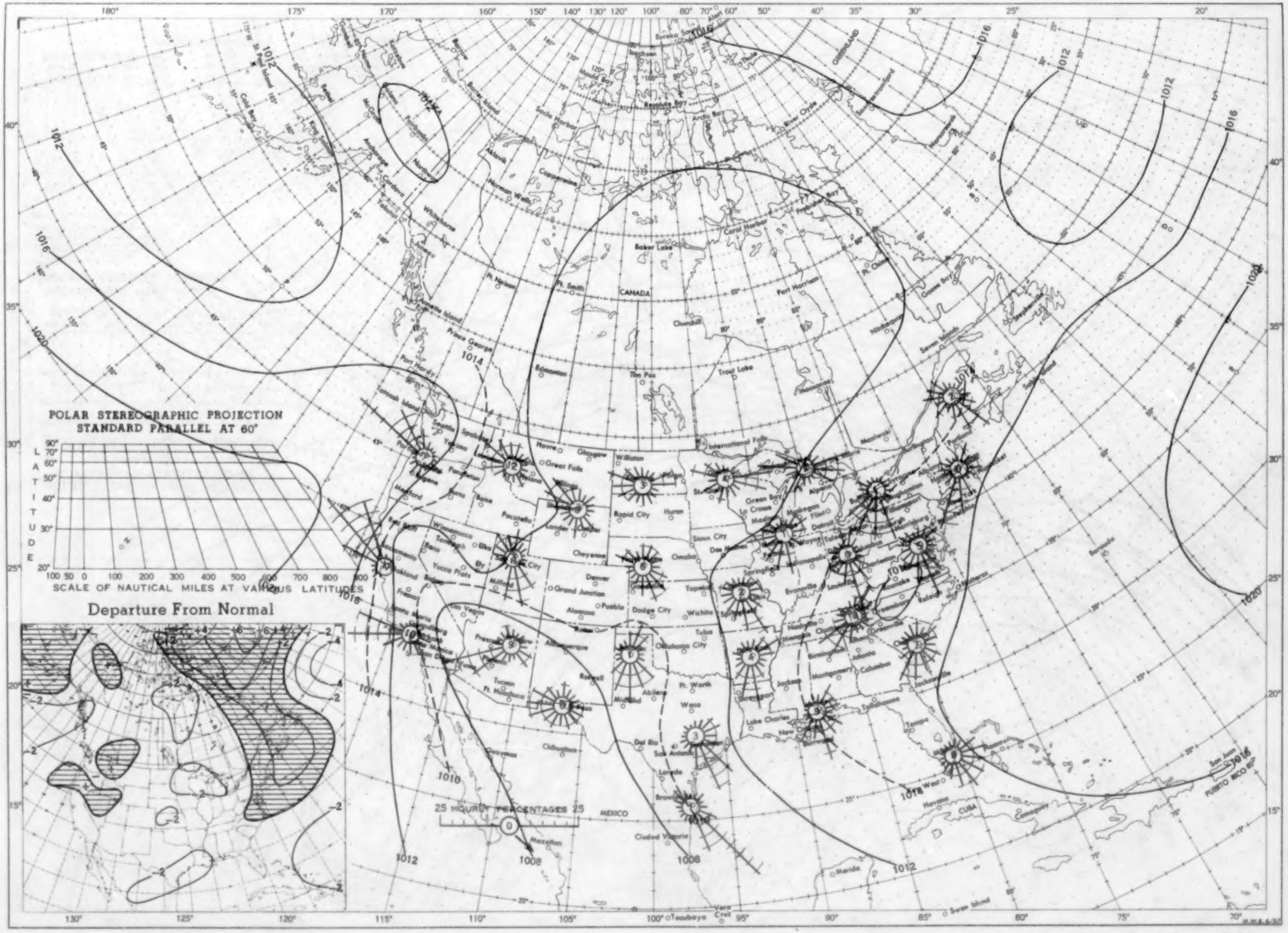
Circle indicates position of center at 7:00 a. m. E. S. T. Figure above circle indicates date, figure below, pressure to nearest millibar. Dots indicate intervening 6-hourly positions. Squares indicate position of stationary center for period shown. Dashed line in track indicates reformation at new position. Only those centers which could be identified for 24 hours or more are included.

Chart X. Tracks of Centers of Cyclones at Sea Level, June 1957.



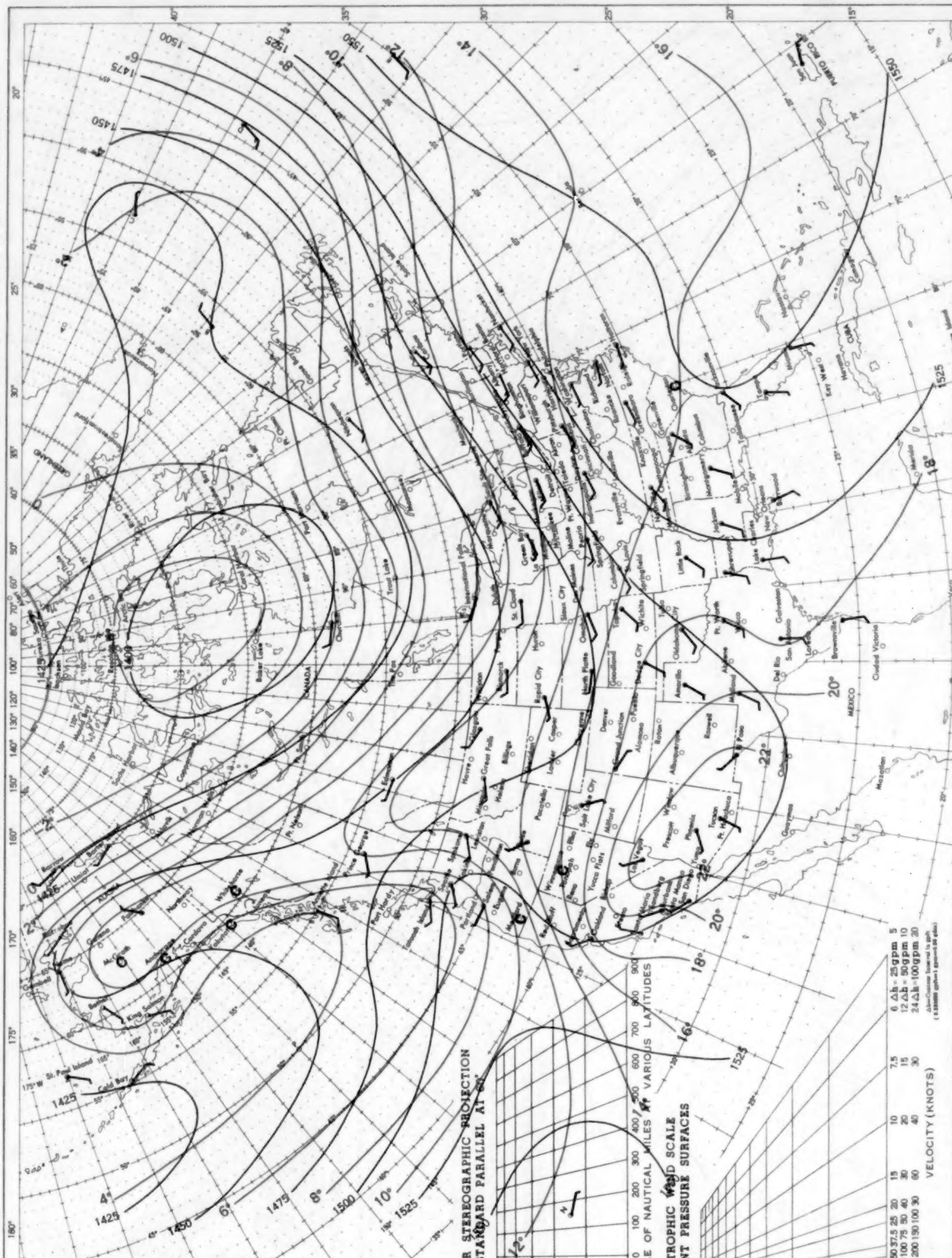
Circle indicates position of center at 7:00 a. m. E. S. T. See Chart IX for explanation of symbols.

Chart XI. Average Sea Level Pressure (mb.) and Surface Windroses, June 1957. Inset: Departure of Average Pressure (mb.) from Normal, June 1957.



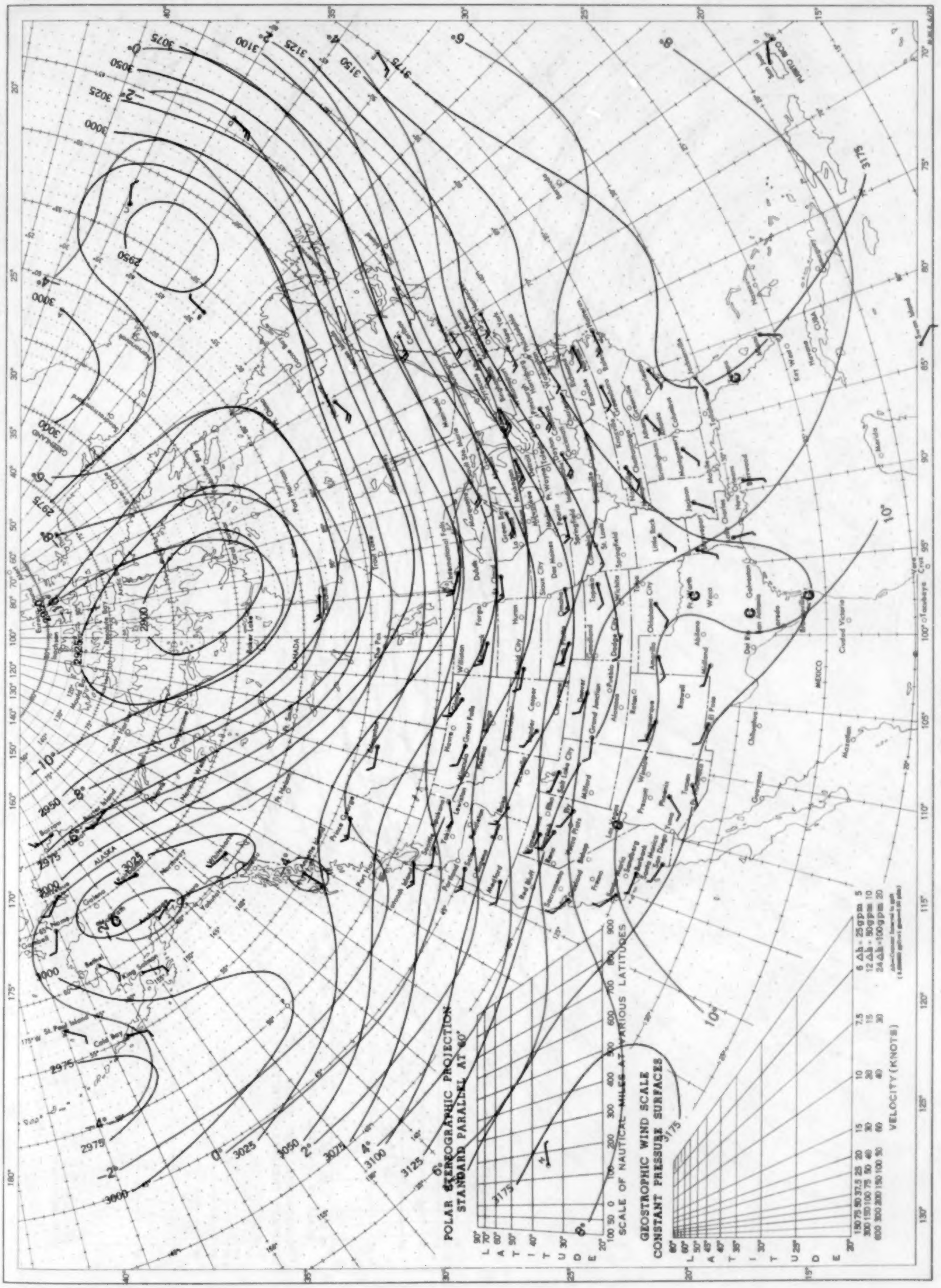
Average sea level pressures are obtained from the averages of the 7:00 a. m. and 7:00 p. m. E. S. T. readings. Windroses show percentage of time wind blew from 16 compass points or was calm during the month. Pressure normals are computed for stations having at least 10 years of record and for 10° intersections in a diamond grid based on readings from the Historical Weather Maps (1899-1939) for the 20 years of most complete data coverage prior to 1940.

Chart XII. 850-mb. Surface, 1200 GMT, June 1957. Average Height and Temperature, and Resultant Winds.



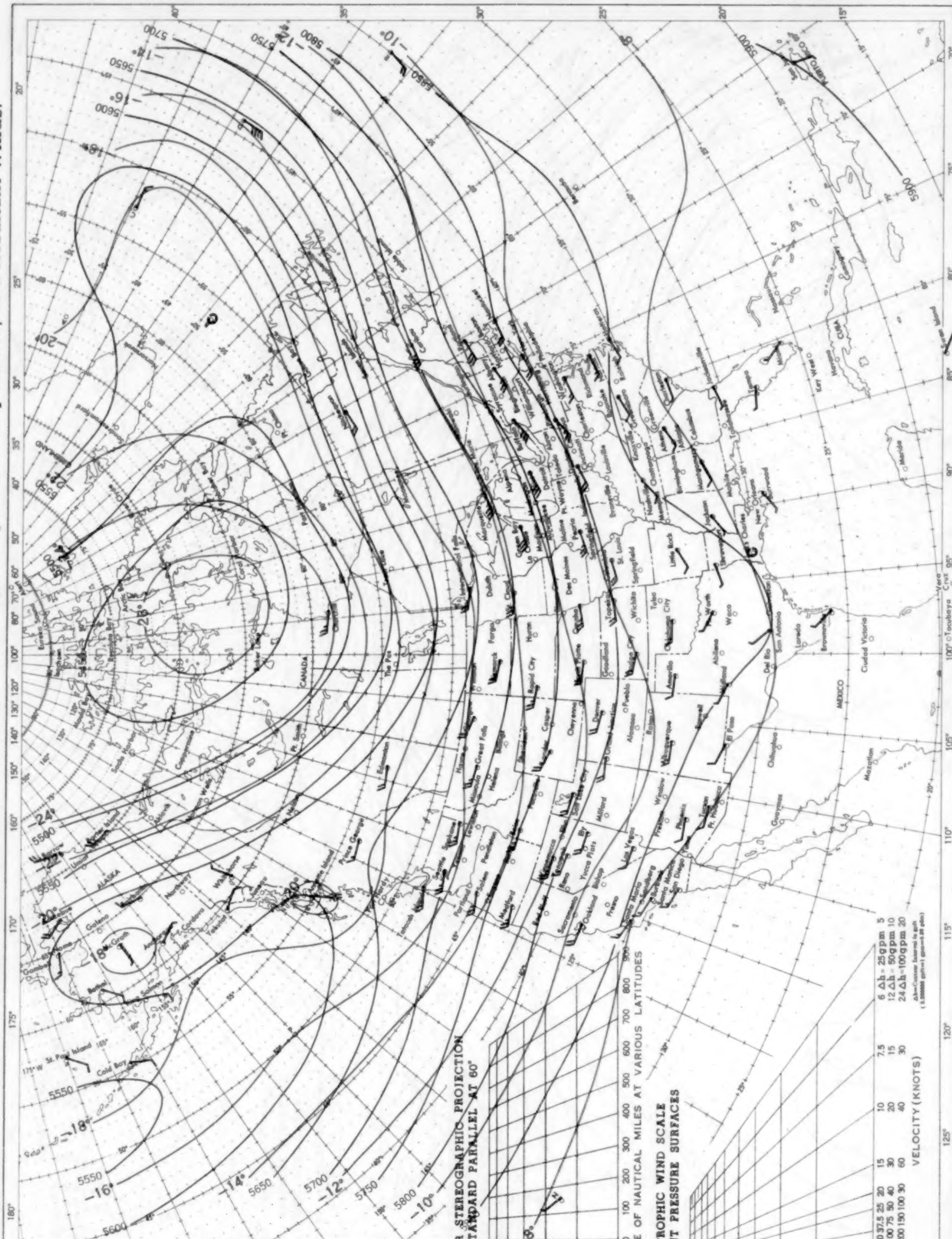
Height in geopotential meters (1 g.p.m. = 0.98 dynamic meters). Temperature in °C. Wind speed in knots; flag represents 50 knots, full feather 10 knots, and half feather 5 knots. All wind data are based on rawin observations.

Chart XIII. 700-mb. Surface, 1200 GMT, June 1957. Average Height and Temperature, and Resultant Winds.



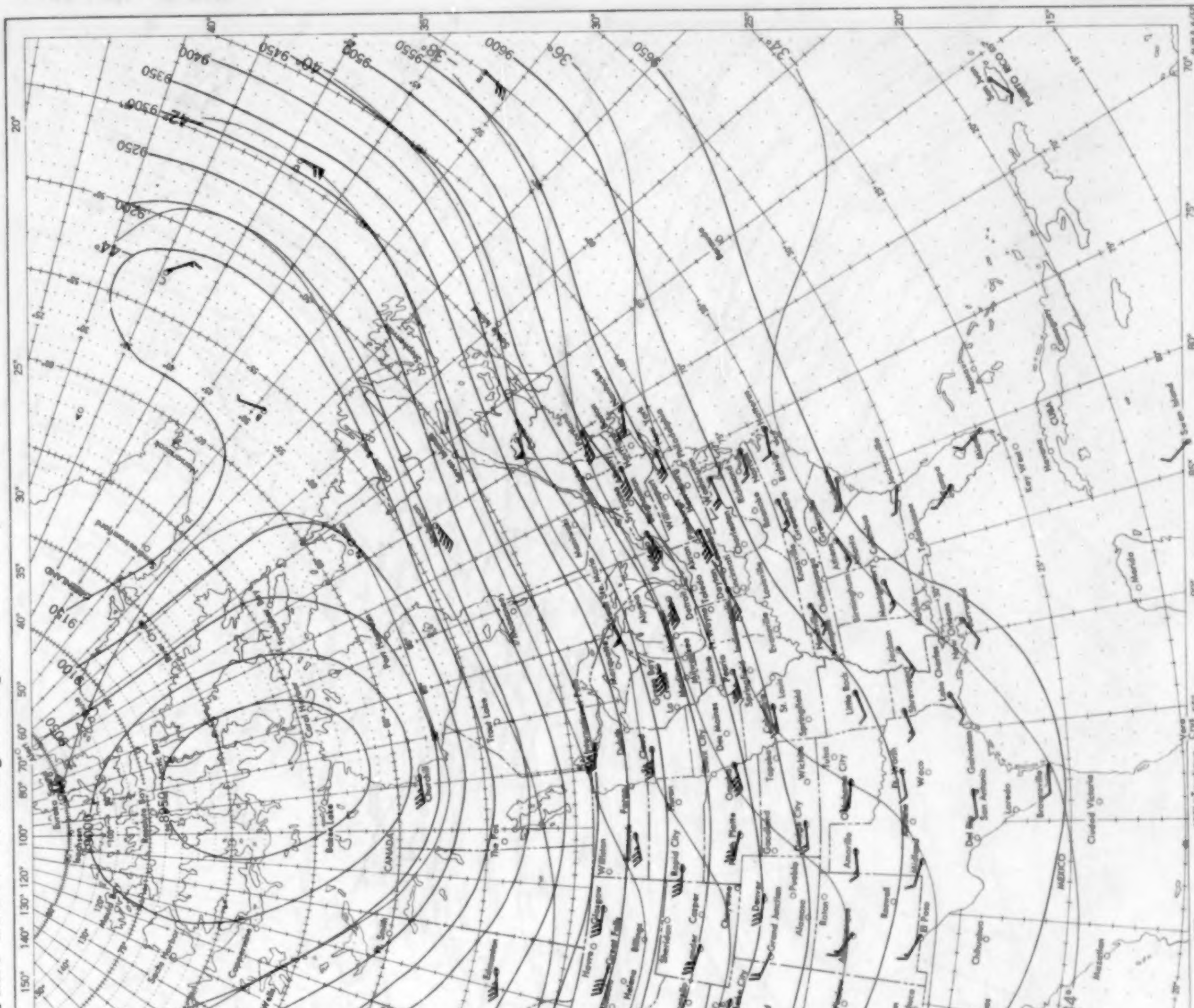
See Chart XII for explanation of map.

Chart XIV. 500-mb. Surface, 1200 GMT, June 1957. Average Height and Temperature, and Resultant Winds.



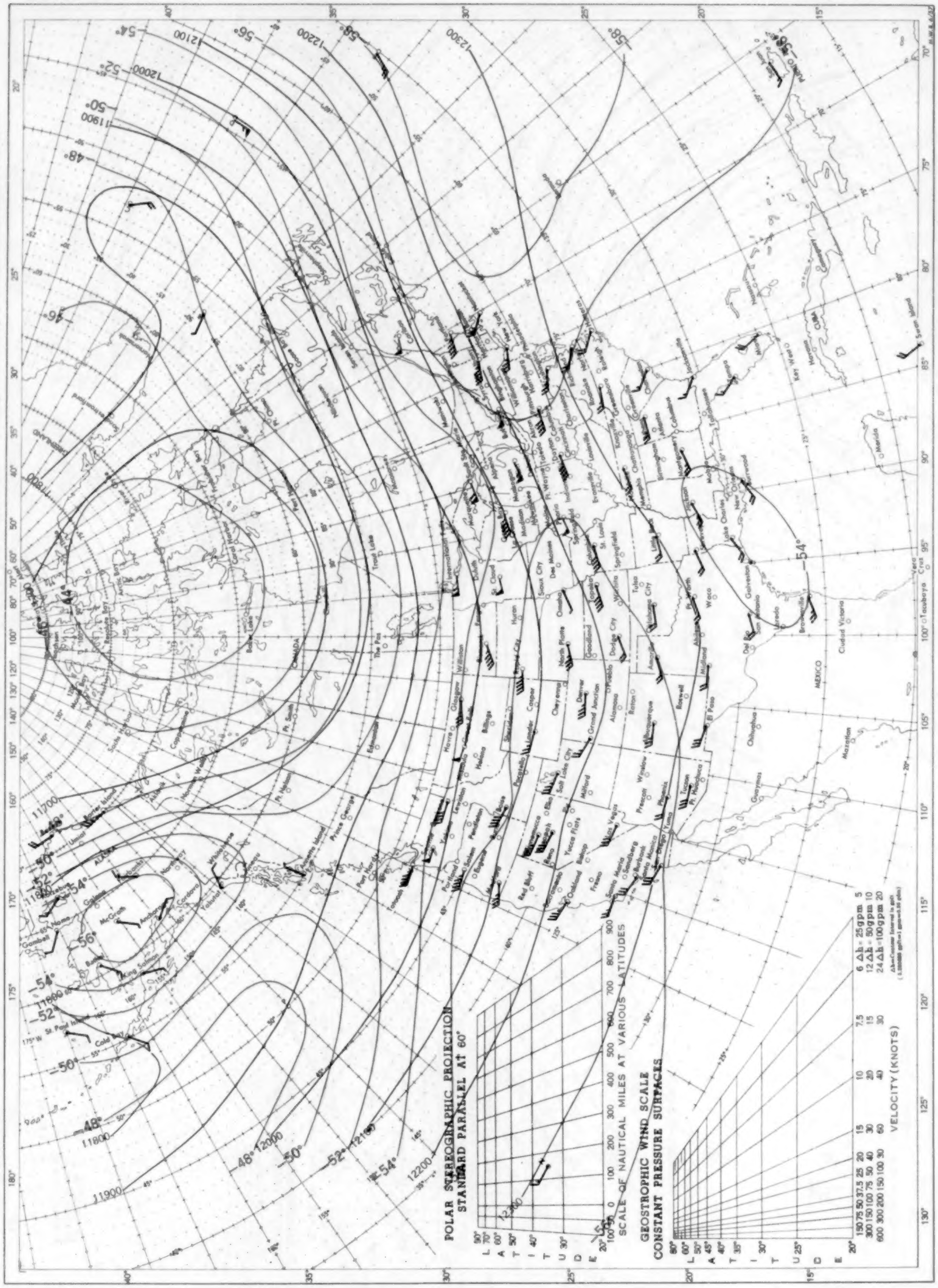
See Chart XII for explanation of map.

Chart XV. 300-mb. Surface, 1200 GMT, June 1957. Average Height and Temperature, and Resultant Winds.



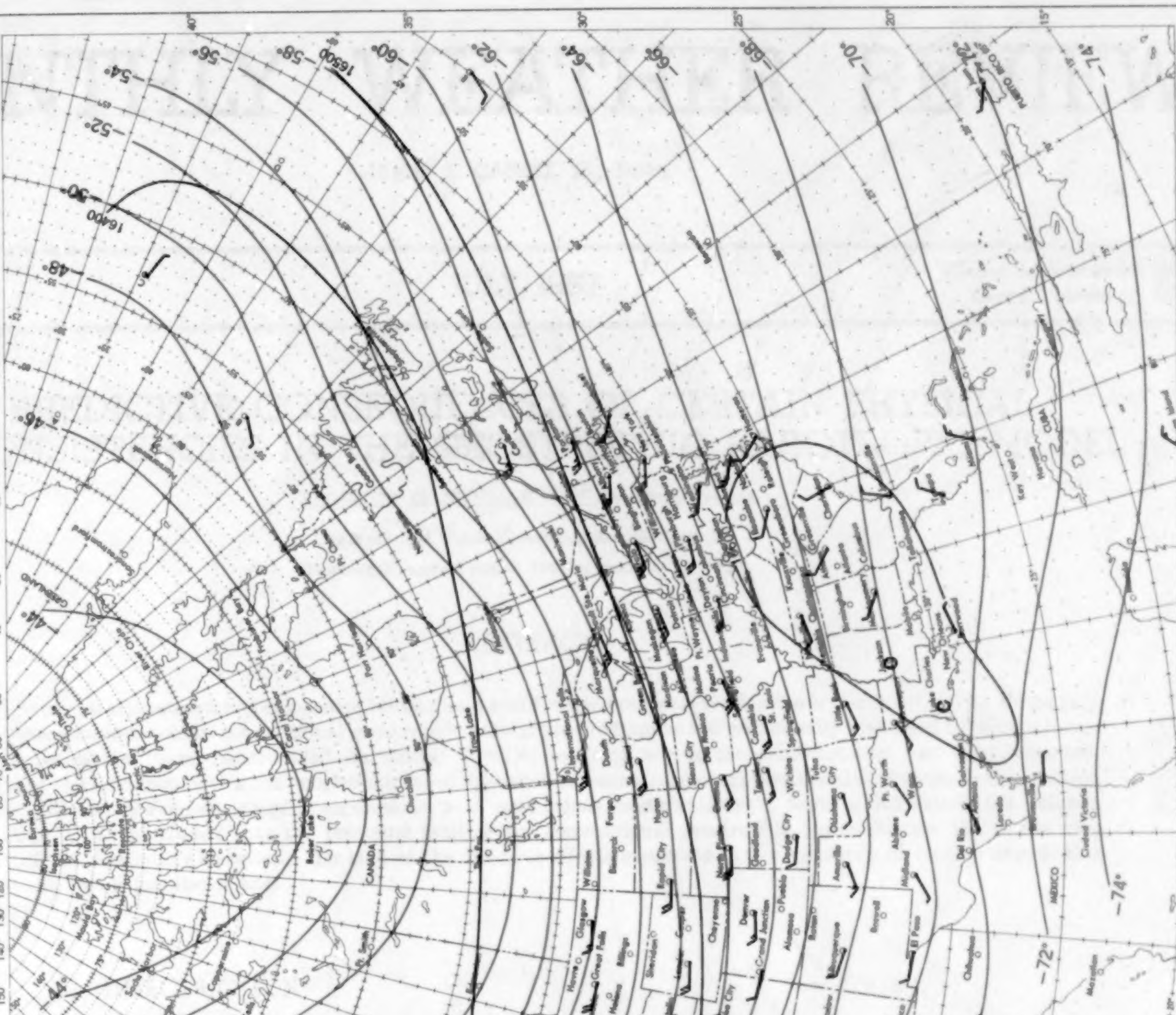
See Chart XII for explanation of map.

Chart XVI. 200-mb. Surface, 1200 GMT, June 1957. Average Height and Temperature, and Resultant Winds.



See Chart XII for explanation of map.

Chart XVII. 100-mb. Surface, 1200 GMT, June 1957. Average Height and Temperature, and Resultant Winds.



See Chart XII for explanation of map.